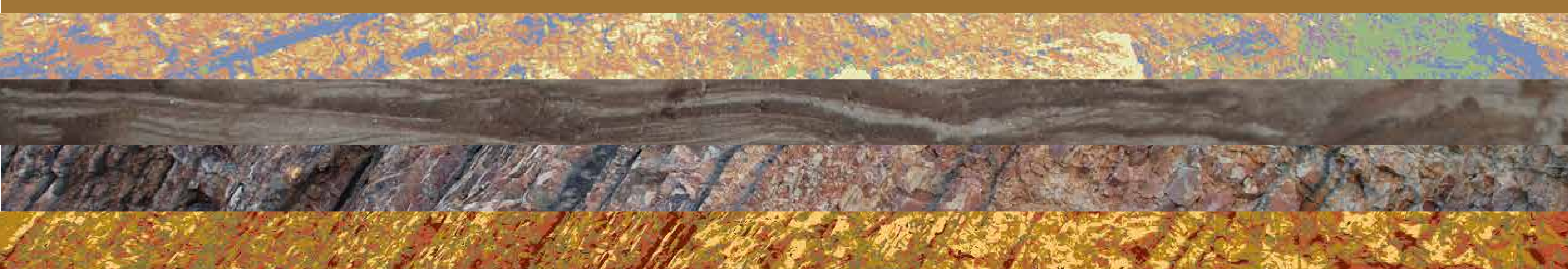
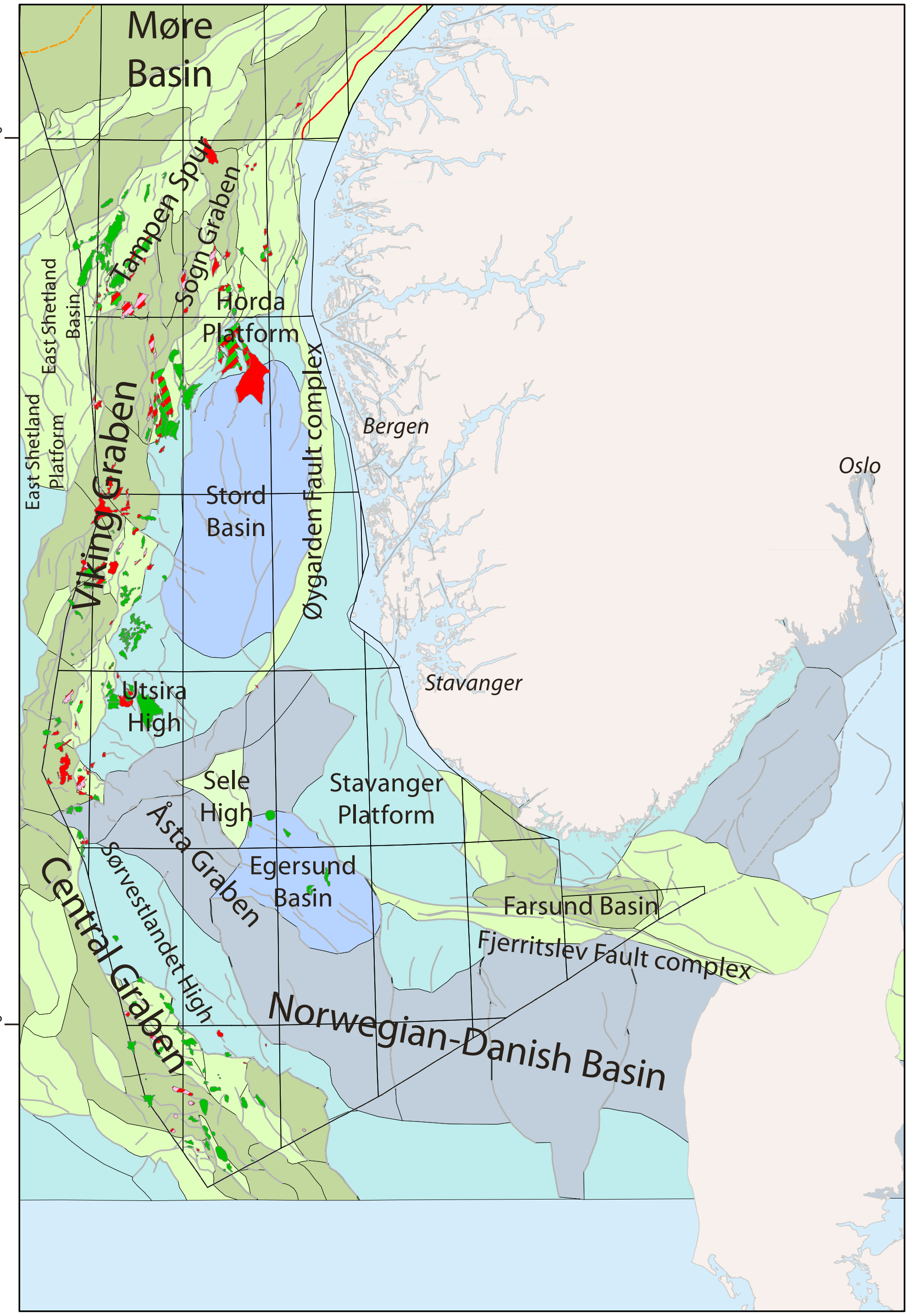
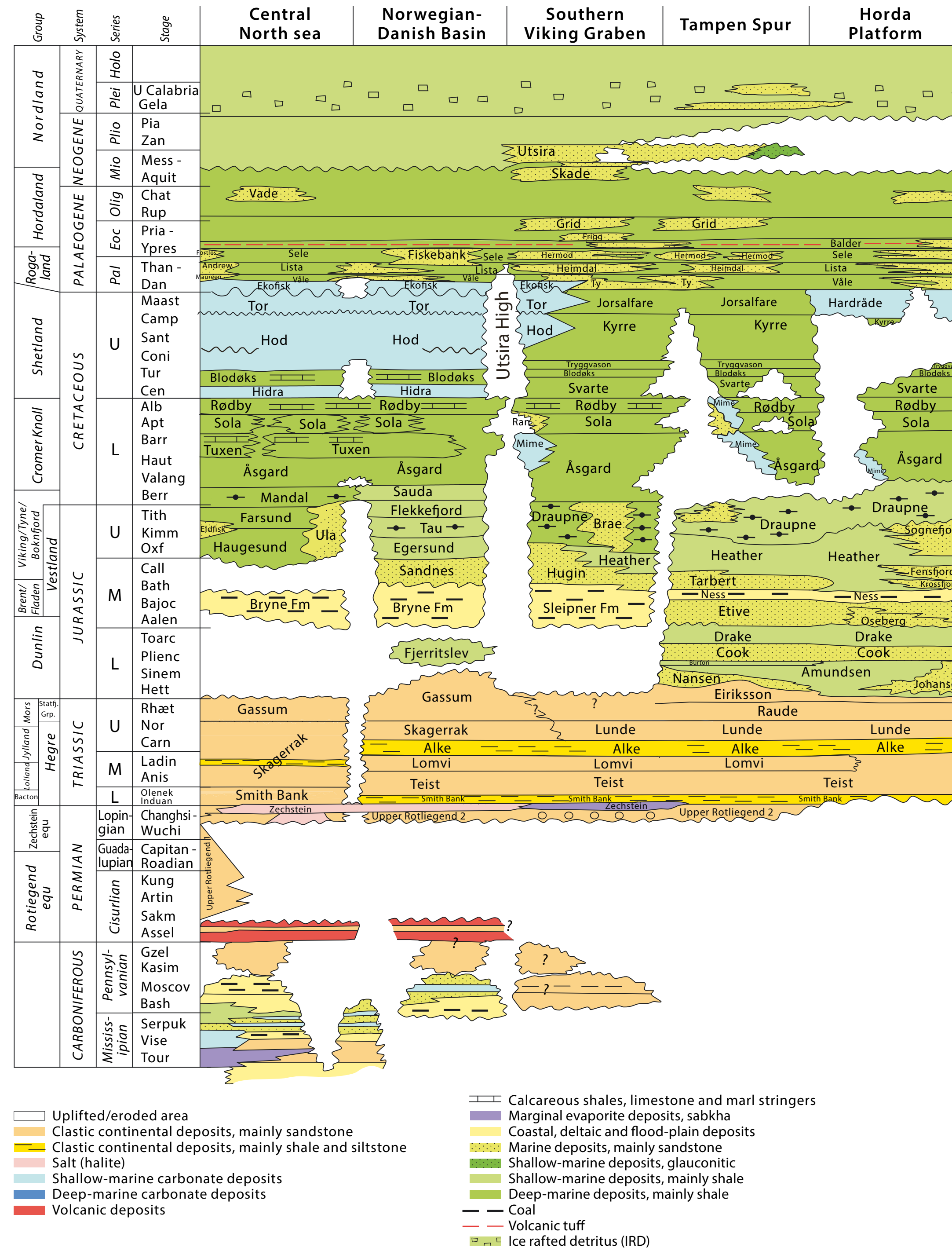
4. The Norwegian North Sea



Eva K. Halland (Project Leader), Ine Tørneng Gjeldvik, Wenche Tjelta Johansen, Christian Magnus, Ida Margrete Meling, Stig Pedersen, Fridtjof Riis, Terje Solbakk, Inge Tappel

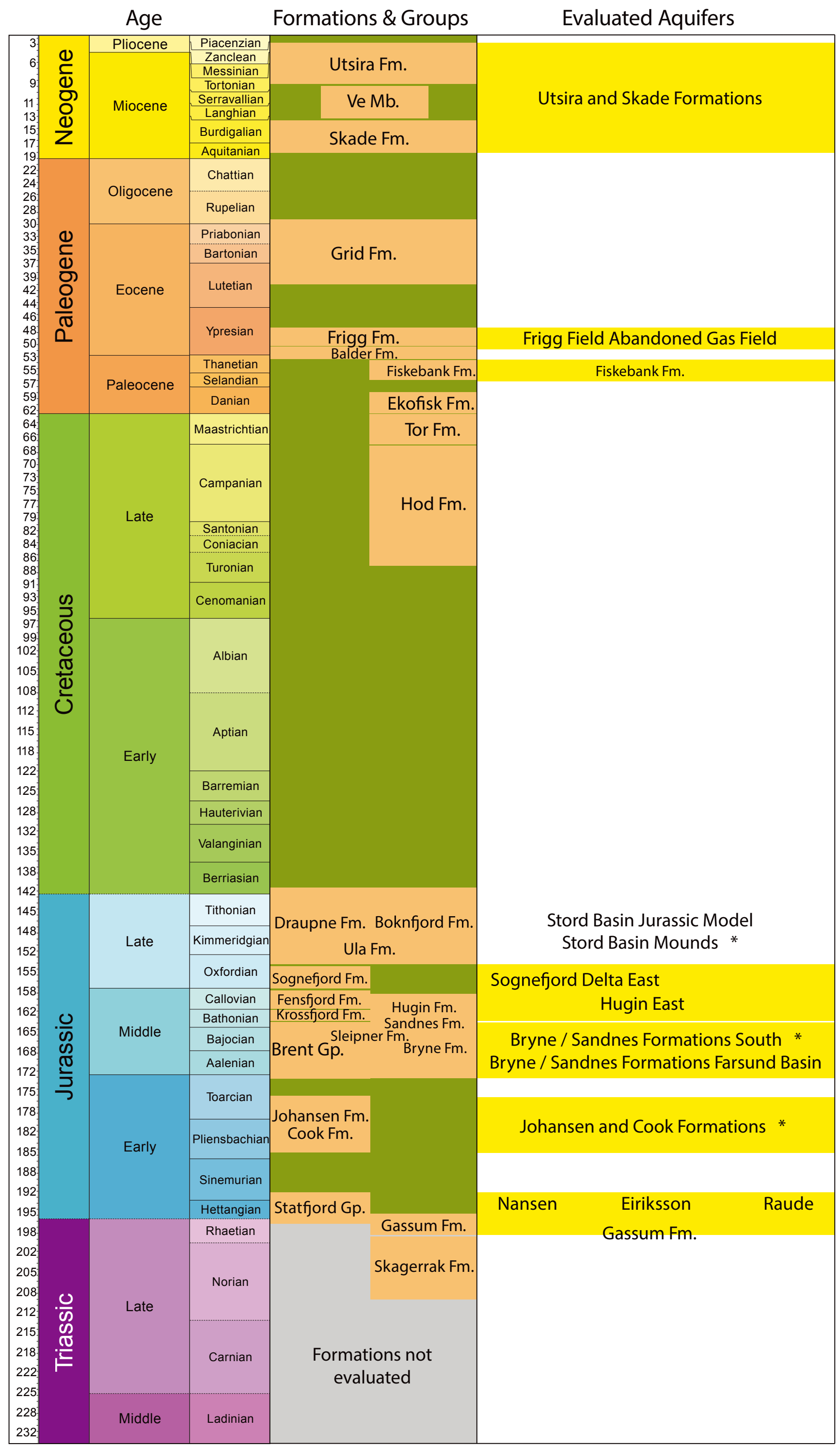
4.1 Geology of the North Sea



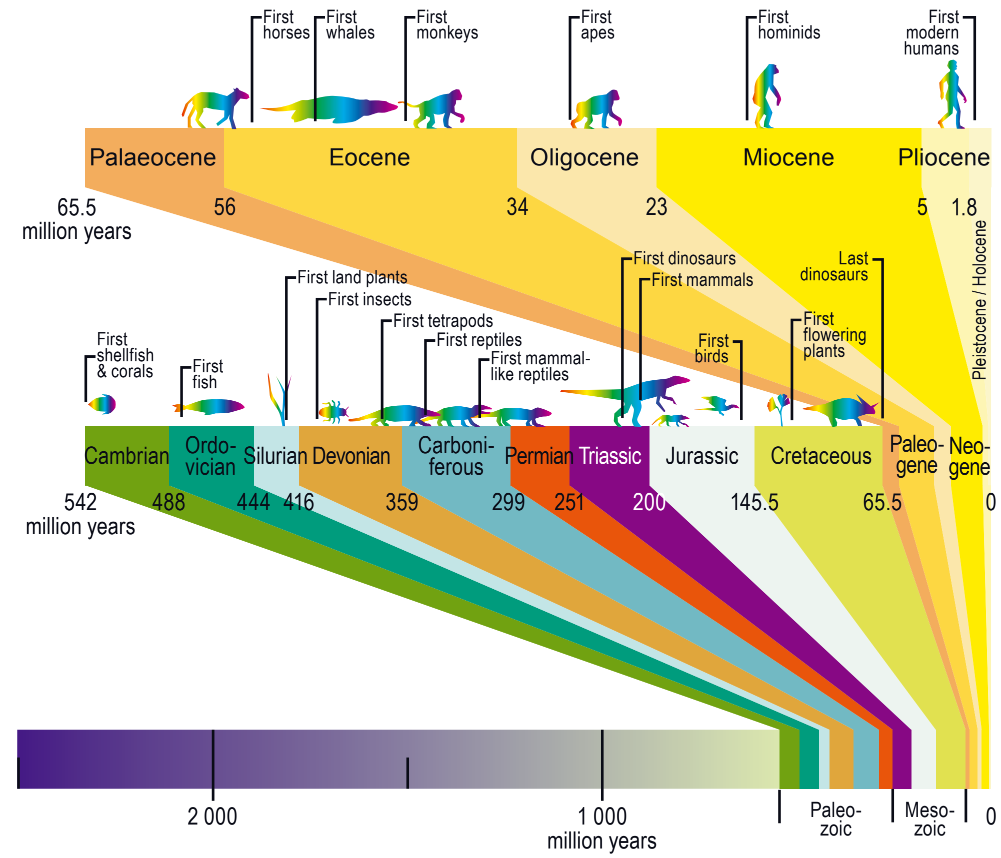


Lithostratigraphic chart of the North Sea (NPD)

4.1 Geology of the North Sea



* Evaluated prospects



Geological time scale

4.1 Geology of the North Sea

The basic structural framework of the North Sea is mainly the result of Upper Jurassic/ Lower Cretaceous rifting, partly controlled by older structural elements.

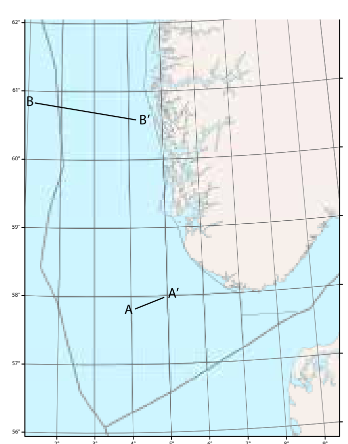
Carboniferous-Permian: Major rifting with volcanism and deposition of reddish eolian and fluvial sandstones (Rotliegendes). Two basins were developed with deposition of thick evaporate sequences (Zechstein). When overlain by a sufficient amount of younger sediments, buoyancy forces caused the salt to move upwards (halokinesis). This is important for generation of closed structures, including hydrocarbon traps, in the southern part of the North Sea and also as a control on local topography and further sedimentation.

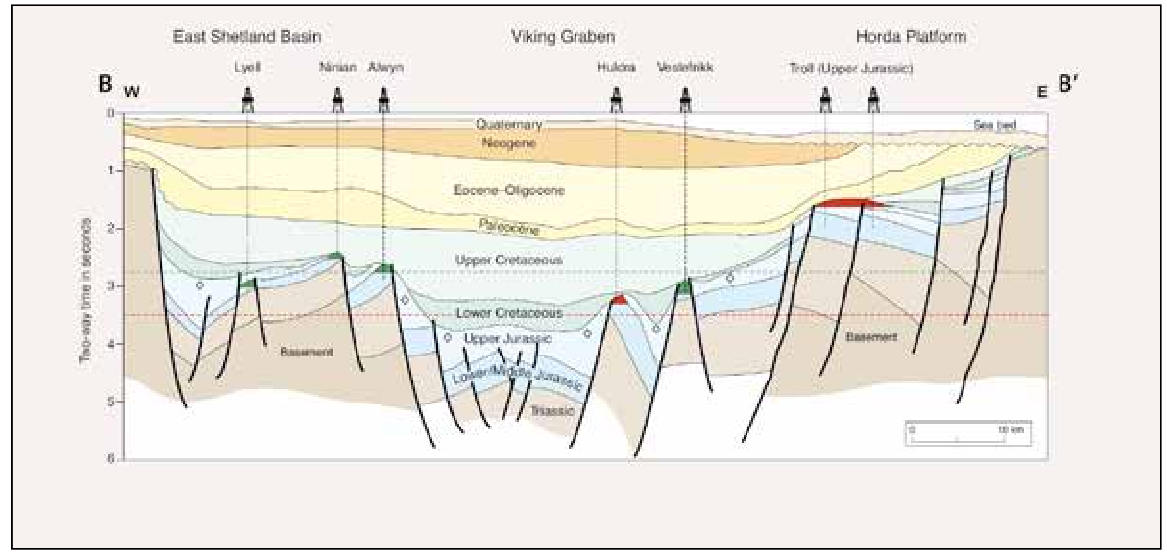
Triassic: Major N-S to NE-SW rifting with thick coarse fluvial sediments deposited along rift margins, grading into finer-grained river and lake deposits in the center of the basins. The transition between the Triassic and Jurassic is marked by a widespread marine transgression from north and south.

Jurassic: The marine transgression was followed by the growth of a volcanic dome centered over the triple point between the Viking Graben, the Central Graben and the Moray Firth Basin. The doming caused uplift and erosion, and was followed by rifting. Large deltaic systems containing sand, shale and coal were developed in the northern North Sea and the Horda Platform (Brent Group). In the Norwegian-Danish Basin and the Stord Basin, the Vestland Group contains similar deltaic sequences overlain by shallow marine/ marginal marine sandstones. The most important Jurassic rifting phase in the North Sea area took place during the Late Jurassic and lasted into the Early Cretaceous. During this tectonic episode, major block faulting caused uplift and tilting, creating considerable local topography with erosion and sediment supply. In anoxic basins thick sequences of shale accumulated, producing the most important source rock and also the Draupne Formation, which is an important seal for hydrocarbon traps in the North Sea area.

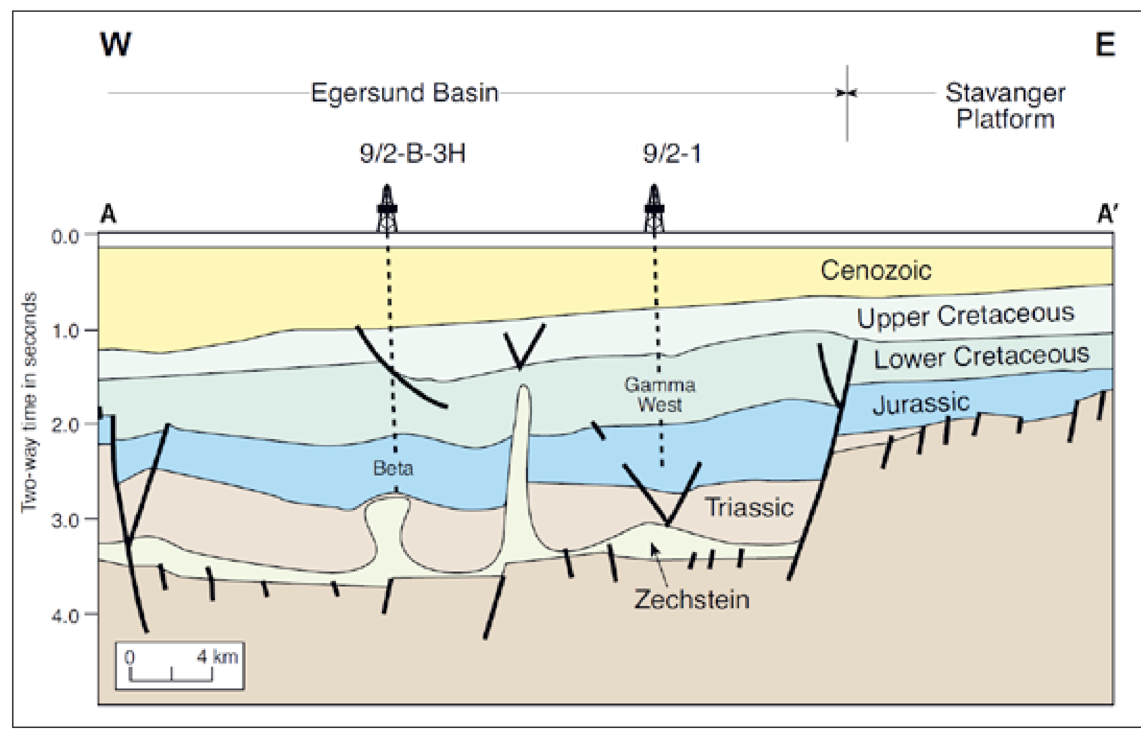
Cretaceous: The rifting ceased and was followed by thermal subsidence. The Upper Cretaceous in the North Sea is dominated by two contrasting lithologies. South of 61º N there was deposition of chalk, while to the north the carbonates gave way to siliclastic, clay-dominated sediments.

Cenozoic: In the Paleocene/Eocene there were major earth movements with the onset of sea floor spreading in the north Atlantic and mountain building in the Alps/Himalaya. In the North Sea, deposition of chalk continued until Early Paleocene. Uplift of basin margins, due to inversion, produced a series of submarine fans transported from the Shetland Platform towards the east. These sands interfinger with marine shales in both the Rogaland and the Hordaland Groups. In the Miocene a deltaic system had developed from the Shetland Platform towards the Norwegian sector of the North Sea, and is represented by the Skade and Utsira Formations. Due to major uplift and Quaternary glacial erosion of the Norwegian mainland, thick sequences were deposited into the North Sea during the Neogene. This led to burial of the Jurassic source rocks to depths where hydrocarbons could be generated and the seals were effective.



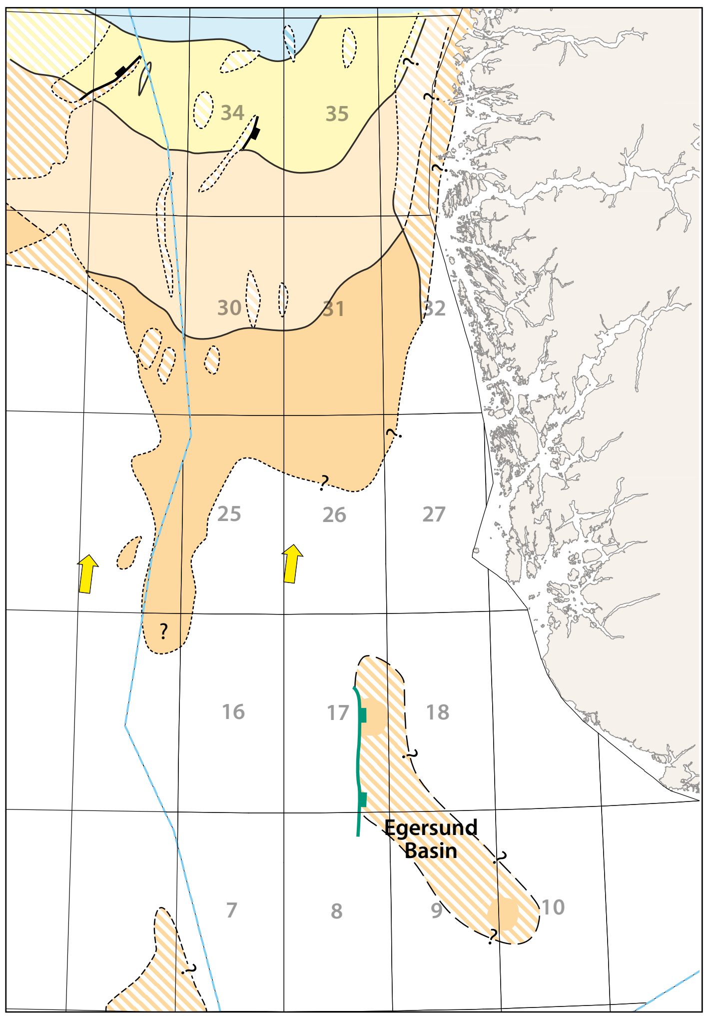


Geoseismic cross section in the northern North Sea. From the Millennium atlas 2001

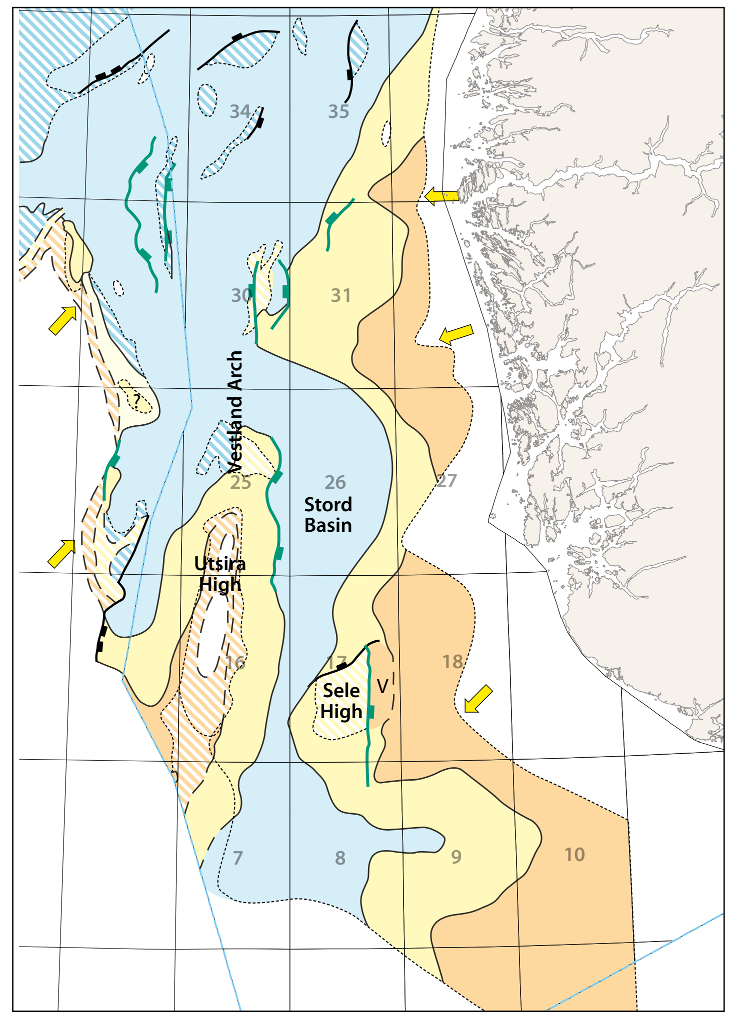


Geoseismic cross section in the Egersund basin. From the Millennium atlas 2001

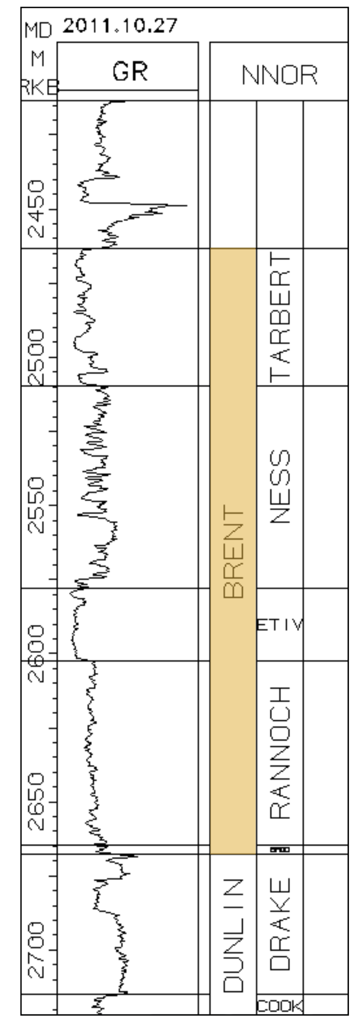
FACIESMAP Bajocian



FACIESMAP Mid- to late Callovian

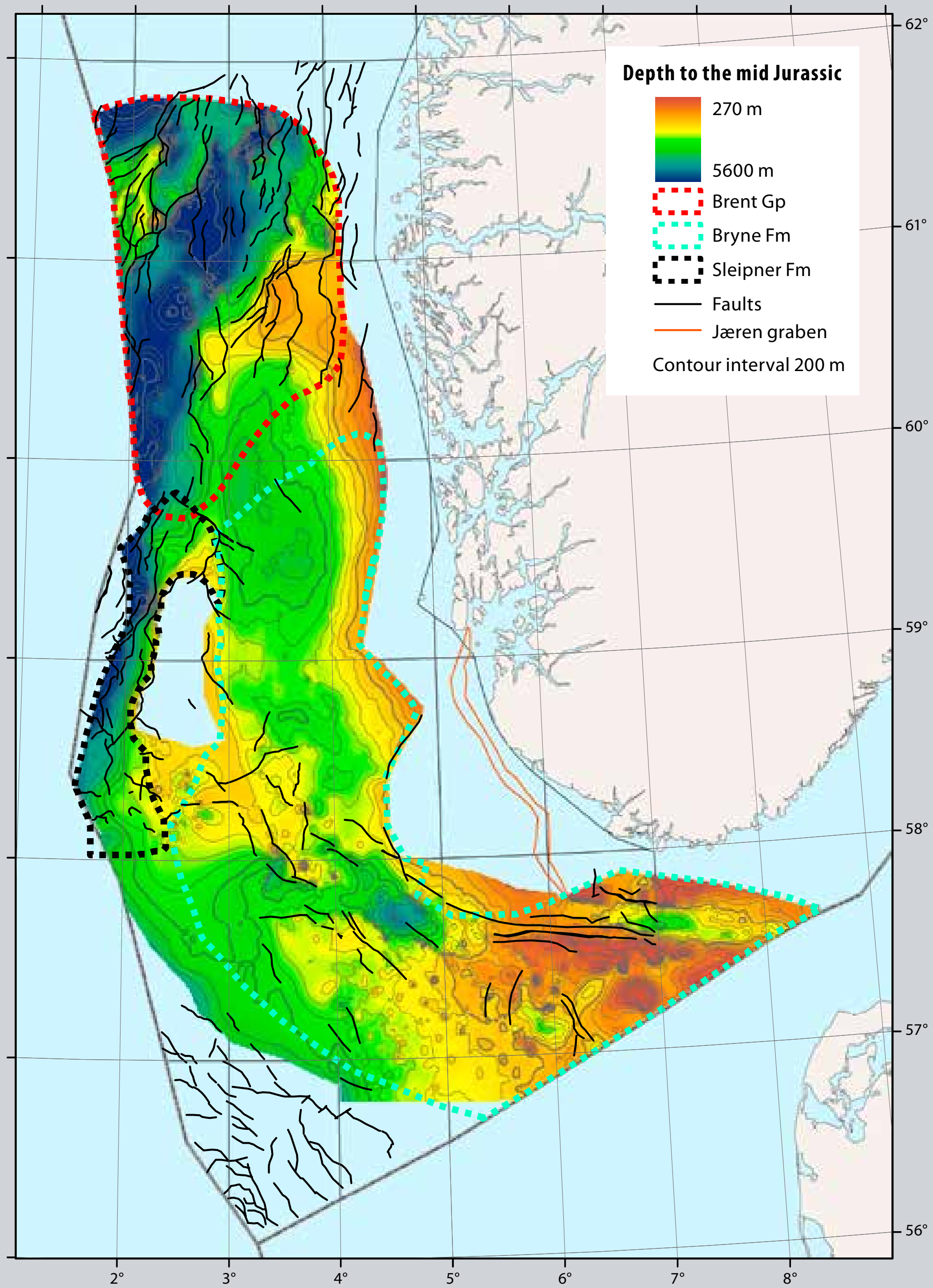


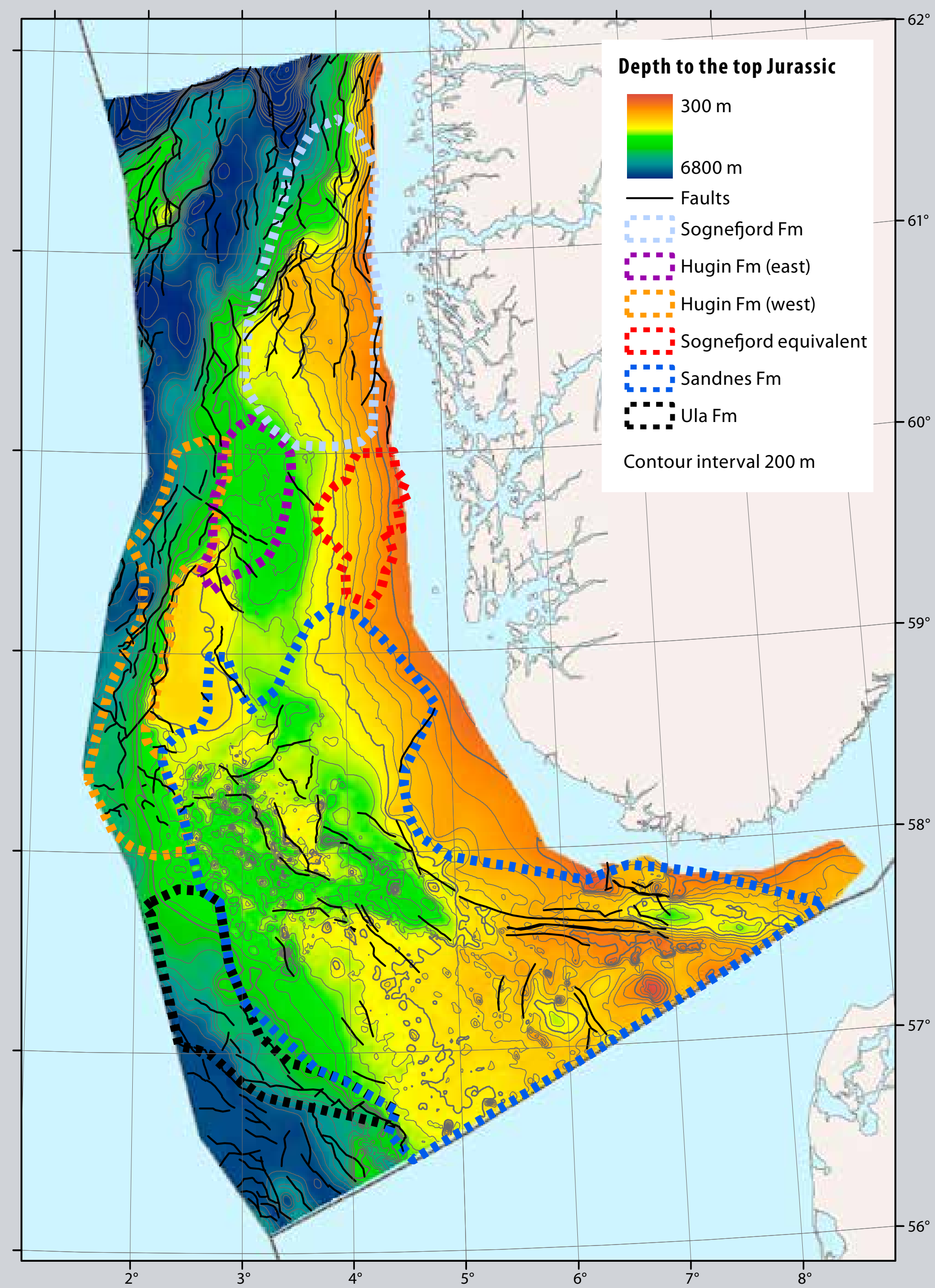
WELL LOG 33/9-1



Examples of mid Jurassic relationship between continental and marine deposits in central and northern North Sea. Continental sediments in brownish colour, shallow marine in yellow and offshore marine in blue.

The map to the left displays the development of the Brent delta and the early stage of the deposition of the Bryne Formation. The map to the right shows the development of the Sognefjord delta and the Sandnes and Hugin Formations after the Brent delta was transgressed.





Mapping of the upper and middle Jurassic forms the basis of many of the following depth and thickness maps of assessed geological formations.
The top Jurassic refers to the top of Upper Jurassic sandstones or their equivalents.

The Statfjord Group

Uppermost Triassic and Lower Jurassic
(Rhaetian to Sinemurian)

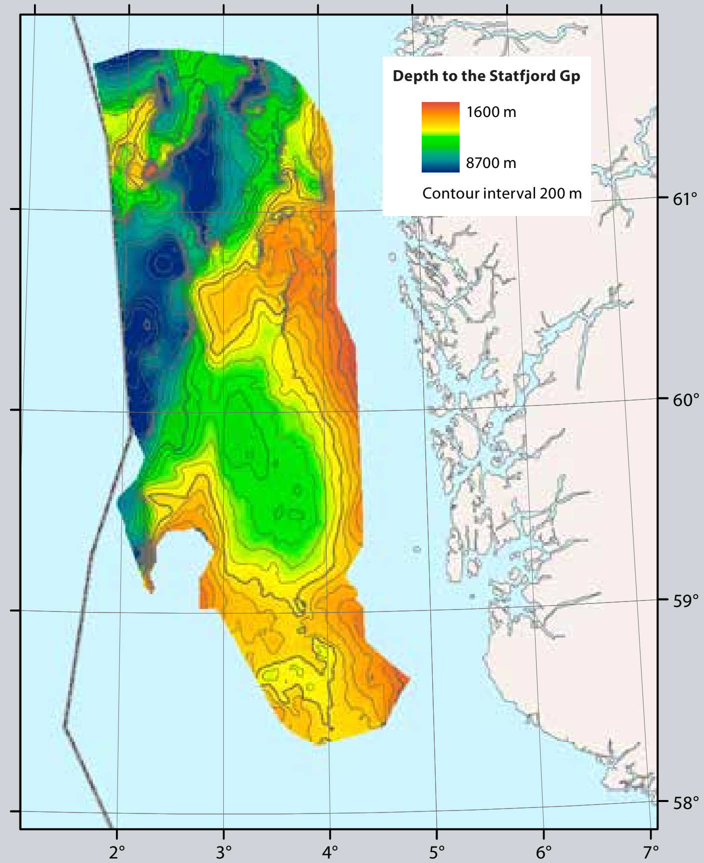
In the type well (33/12-2) the base of the Statfjord Gp is defined at the transition from the fining upward mega-sequence of the Lunde Fm and a coarsening upward mega-sequence of the Statfjord Gp. The Statfjord Gp is sub-divided into three formations (Raude, Eiriksson and Nansen). The upper boundary of the Statfjord Gp is sharp against the fully marine mudstones of the overlying Dunlin Group that could act as a regional seal.

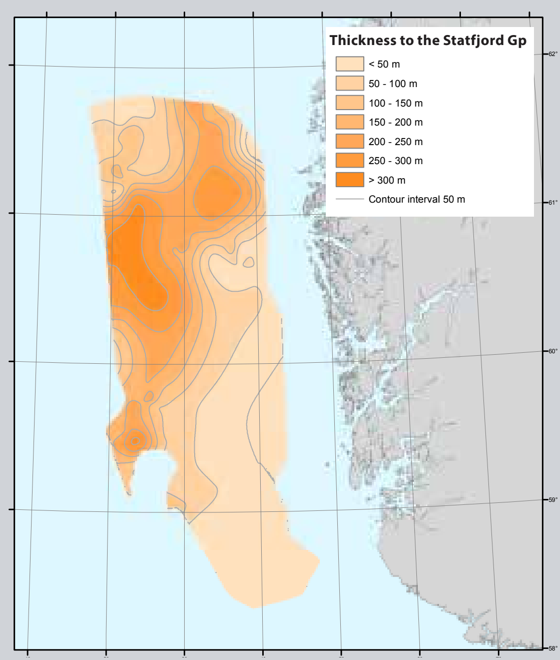
The Statfjord Gp can be recognized in the entire area between the East Shetland Platform to the west and the Øygarden Fault Complex against the Fennoscandian Shield to the east. To the south the Statfjord Gp has been recognized as far south as Norwegian blocks 25/8 and 11, and has not to date been identified north of the Tampen Spur. Thickness from wells in the type area varies from 140 m to 320 m. The Statfjord Gp displays large thickness variations due to regional differential subsidence as seen in a NW-SE traverse from the Tampen Spur to the Horda Platform. The Statfjord Group is relatively thin in the Tampen area (140 m). On the Snorre Field it increases across the Viking Graben and thins on the Horda Platform towards the Norwegian mainland.

Depositionally, the Statfjord Gp records the transition from a semi-arid, alluvial plain (Raude Fm) to dominantly fluvial sandstones (Eiriksson and Nansen fms) with occasional marine influence in the upper part (Nansen Fm). Generally the formation is buried in excess of 2000 m.

In the Snorre Field where the crest of the structure is 2335 m, porosities between 16-28% and permeabilities in the order of 250-4000 mD have been reported.

The Gassum Fm in the Norwegian-Danish Basin is time equivalent to the Statfjord Gp.





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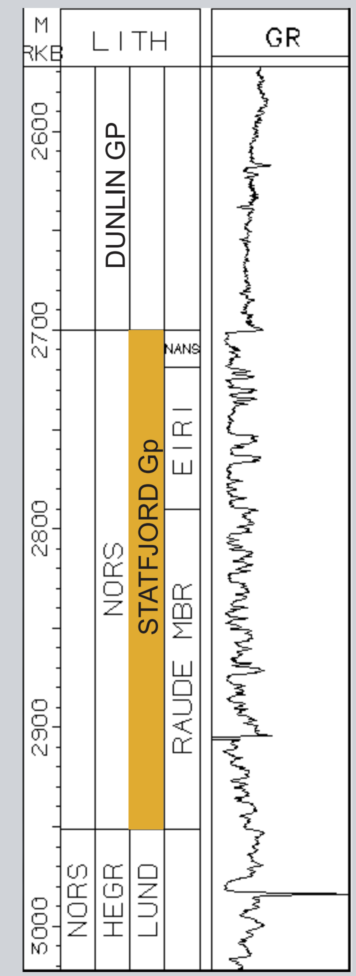


Core photo well 34/7-13, 2873-2878 m

The Dunlin Group

Lower to Middle Jurassic
(Hettangian to Bajocian)

The Dunlin Gp represents a major marine transgressive sequence overlying the Statfjord Gp. It is divided into five formations; the Amundsen, Johansen, Burton, Cook and Drake fms. The type well is well 211/29-3 (British side), and well 33/9-1 is a Norwegian reference well. The Amundsen, Burton and Drake Fm are mainly silt and marine mudstones, while the Johansen and Cook fm are mainly marine/marginal marine sandstones. The upper boundary is the deltaic sequences of the Brent Gp.

The group is recognized over most of the East Shetland Basin, fringing the East Shetland Platform, and the northern part of the Horda Platform. To the south the Dunlin Gp has been recognized in wells as far south as 59°N. In the type well, the thickness is 222 m and in the reference well the thickness is 255 m. The Dunlin Gp has its maximum thickness (possible 1000 m) in the axial part of northern Viking Graben, and a thickness of more than 600 m has been drilled in the western part of the Horda Platform (well 30/11-4).

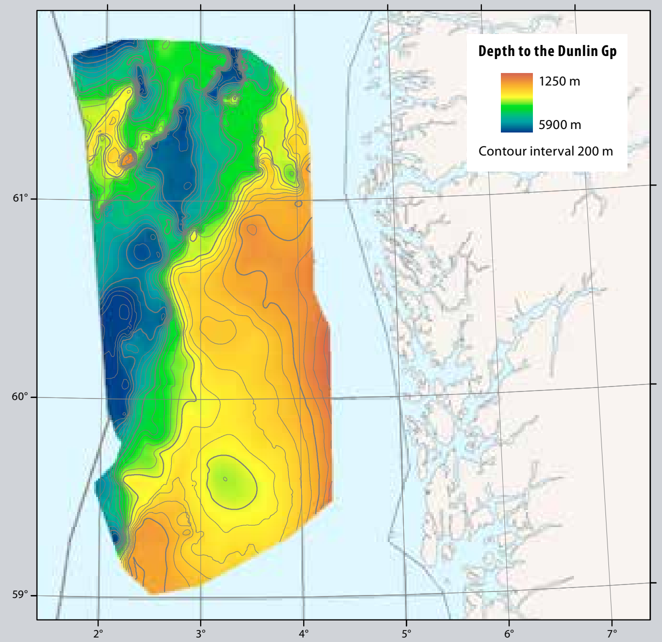
The Amundsen Fm (Sinemurian to Pliensbachian) contains mainly marine silts and mudstones deposited on a shallow marine shelf. It is distributed widely in the East Shetland Basin and in the northern Viking Graben, forming a seal to the underlying Statfjord Gp and possibly to the Johansen Fm.

The Johansen Fm (Sinemurian to Pliensbachian) sandstones split the Amundsen Fm in an area restricted to the eastern part of the Horda Platform (well 31/2-1), and the formation can be mapped northwards to approximately 600 N. The Johansen Fm is interpreted in terms of deposition on a high energy shallow marine shelf with sediment input from the east.

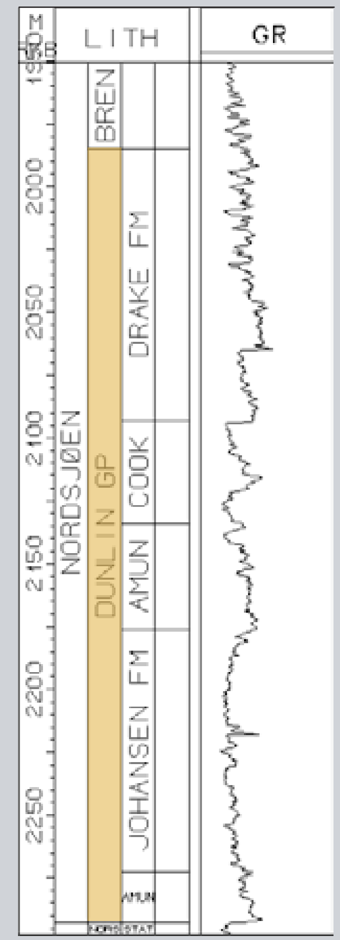
The Burton Fm (Sinemurian to Pliensbachian) is mainly marine mudstones that overlie the Amundsen Fm. This formation is found over most of the area, but it is not present on the Horda Platform. It forms mainly basinal facies and passes into the Amundsen Fm towards the margins.

The Cook Fm (Pliensbachian to Toarcian) is dominated by sandstone tongues that interfinger with the Drake mudstones at several distinct stratigraphic levels. Typically each of the sandstones are characterized by a lower zone of sharp-based, upward-coarsening shoreface sand and siltstones and an upper erosive surface consisting of thin tidal flat and thick deltaic/estuarine sandstones.

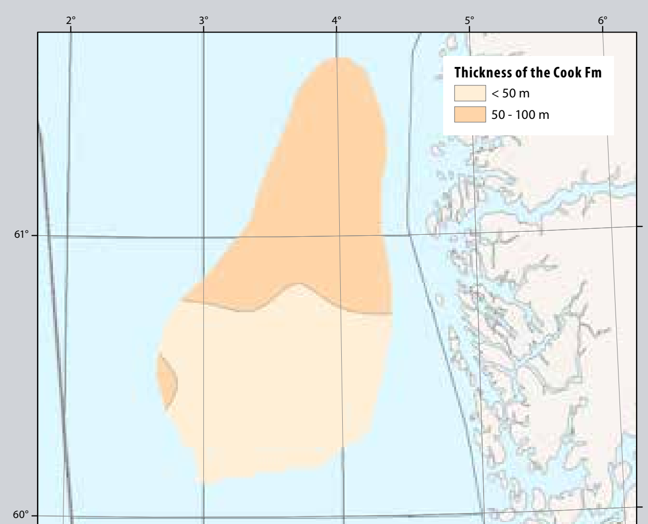
The Drake Fm (Toarcian to Bajocian) consisting of silt and mudstones were deposited during a continued rise in the relative sea level and the formation acts as a seal towards the underlying Cook sandstones. The upper boundary of the Drake Fm is marked by the more sandy sediments at the base of the deltaic Brent Group. Locally there is some sand towards the top of the Drake Fm. A time equivalent to the Dunlin Gp is the Fjerritslev Fm in the Norwegian–Danish Basin.



WELL LOG 31/2-1



Core photo well 34/4-5, 3427-3430 m



The Drake Fm (Toarcian to Bajocian) silts and mudstones were deposited during a continued rise in the relative sea level and the formation acts as a seal towards the underlying Cook sandstones. The upper boundary of the Drake Fm is marked by the more sandy sediments at the base of the deltaic Brent Group. Locally there is some sand towards the top of the Drake Fm.

A time equivalent to the Dunlin Gp is the Fjerritslev Fm in the Norwegian –Danish Basin.

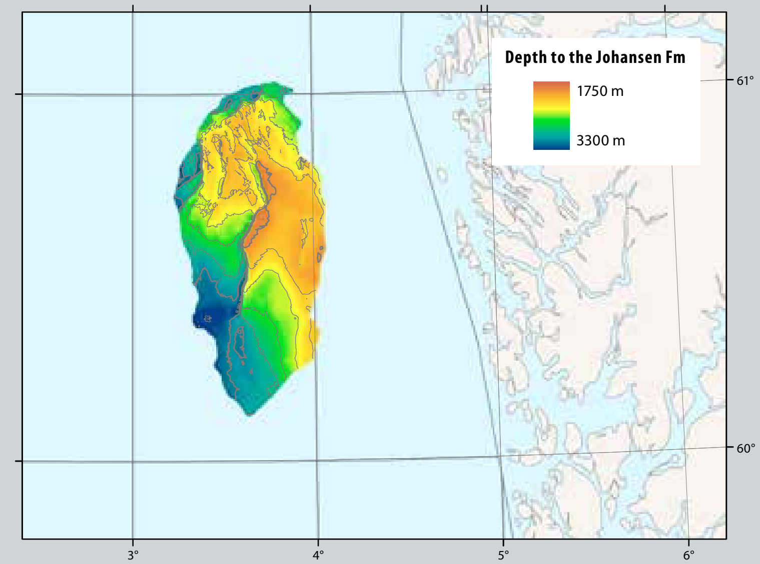
The Dunlin Group - Johansen Formation

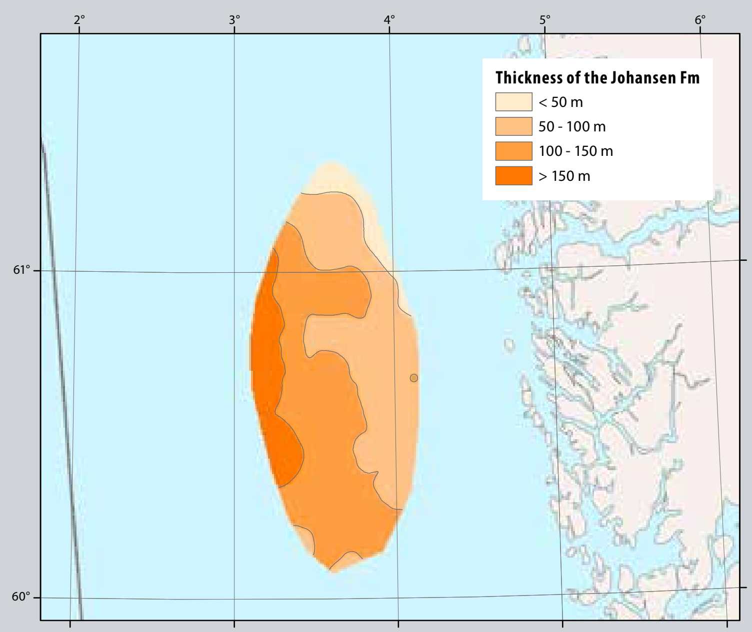
Lower Jurassic
(Sinemurian to Pliensbachian)

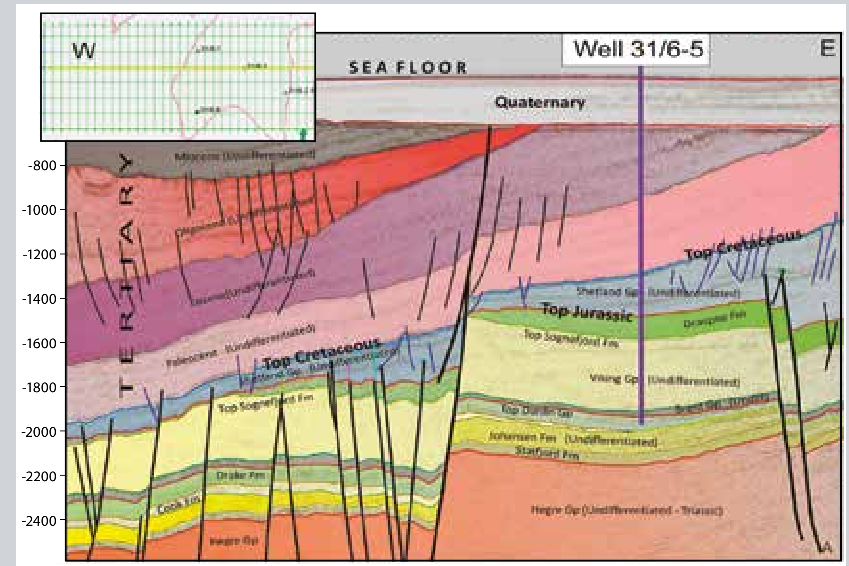
The Johansen Fm has its type area on the Horda Platform (type well 31/-2-1) where the sandstones in the formation interfingers with the marine silt and mudstones of the Amundsen Fm. Thus, the Amundsen Fm might act as a seal for the Johansen Fm.

The Johansen Fm is found in a restricted area extending from the eastern part of the Horda Platform and north towards 62°N.The thickness in the type well is 96 m. In an E-W traverse on the northern part of the Horda Platform the formation thickens to the west towards the northern Viking Graben, where thicknesses in excess of 200 m have been drilled (well 30/11-4). Towards the east the formation thins into a thickness of some tens of meters towards the Øygarden Fault Complex. The Johansen Fm was probably deposited in a high energy shallow marine shelf with sediment input from the East.

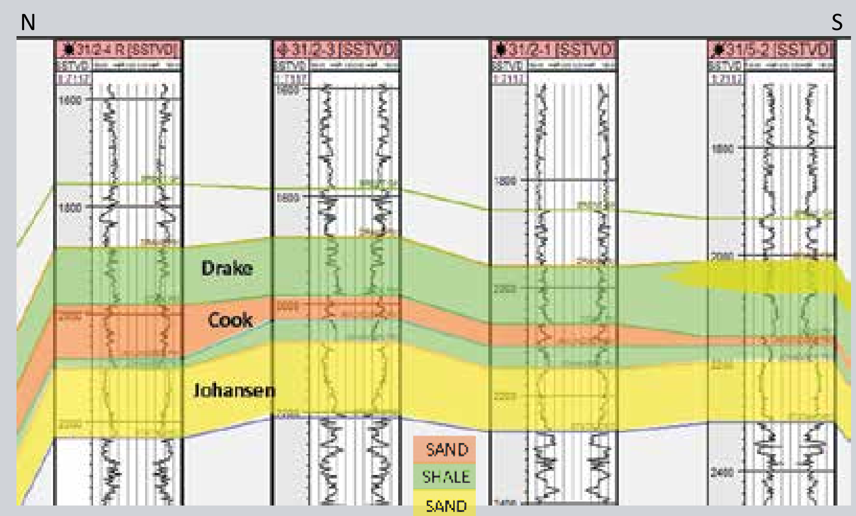
Generally the formation is buried to a depth of more than 2000 m, increasing towards the West into the northern Viking Graben area. In the Troll Field, where the crest of the Johansen Fm is approximately at 2300 m depth, porosity and permeability is in the order of 15-24% and 100-1000 mD respectively.







Gassnova




Core photo well 31/2-3, 2116-2118 m

The Brent Group

Uppermost Lower Jurassic to Middle Jurassic (Upper Toarcian–Bajocian)

The Brent Gp has its type area in the East Shetland Basin and contains five formations; the Broom, Rannoch, Etive, Ness and Tarbert Fm. On the Horda Platform, the Oseberg Fm is defined as part of the Brent Gp. Type and reference well for the Brent Gp is well 211/29-3 (UK) and well 33/9-1. For the Oseberg Fm the type well is 30/6-7. The lower boundary is the marine silts and mudstones of the Dunlin Gp. The upper boundary is the Heather/Draupne Fm marine mudstones of the Viking Group, forming a regional seal.

The Brent Gp is found in the East Shetland Basin and is recognizable over most of the East Shetland Platform and the northern part of the Horda Platform. South of the Frigg area, broadly equivalent sequences to the Brent Gp are defined as the Vestland Group. To the North, the deltaic rocks of the Brent Gp shales out into marine mudstones between 61°30´N and 62° N. The thickness of the group varies considerably due to differential subsidence and post Middle Jurassic faulting and erosion. Variable amounts of the group may be missing, particularly over the crests of rotated fault blocks.

The deposition of the Brent Gp records the outbuilding of a major deltaic sequence from the south and the subsequent backstepping or retreat. The Oseberg sandstones form a number of fan-shaped sand-bodies with a source area to the east. The sandstones in the lower part are deposited in a shallow marine environment, overlain by more alluvial sands and capped by sand which has been reworked by waves.

Due to the Upper Jurassic faulting, uplift/erosion and differential subsidence, the Brent Group is located at a wide range of depths, varying from 1800 m on the Gullfaks Field to more than 3500 m on the Huldra Field. As a result there is a complex distribution of porosity and permeability.

The Broom Fm (Upper Toarcian to Bajocian) is thin and locally developed. It consists of shallow marine, coarse-grained and poorly sorted conglomeratic sandstones and is a precursor for the regressive sequence of the overlying Rannoch Fm.

The Rannoch Fm (Upper Toarcian to Bajocian) in the type area is well-sorted very micaceous sandstones, showing a coarsening upwards motif, deposited as delta front or shoreface sands. The upper boundary is defined by cleaner sandstones of the overlying Etive Fm. The thickness of the Rannoch Fm in the type area varies between 35 and 63 m.

The Etive Fm (Bajocian) contains less micaceous sandstones than the underlying Rannoch Fm. The upper boundary is the first significant shale or coal of the overlying Ness Fm. The depositional environment for the Etive Fm is interpreted as upper shoreface, barrier bar, mouth bar and channel deposits. The thickness of the formation varies considerably from 11 m to more than 50 m.

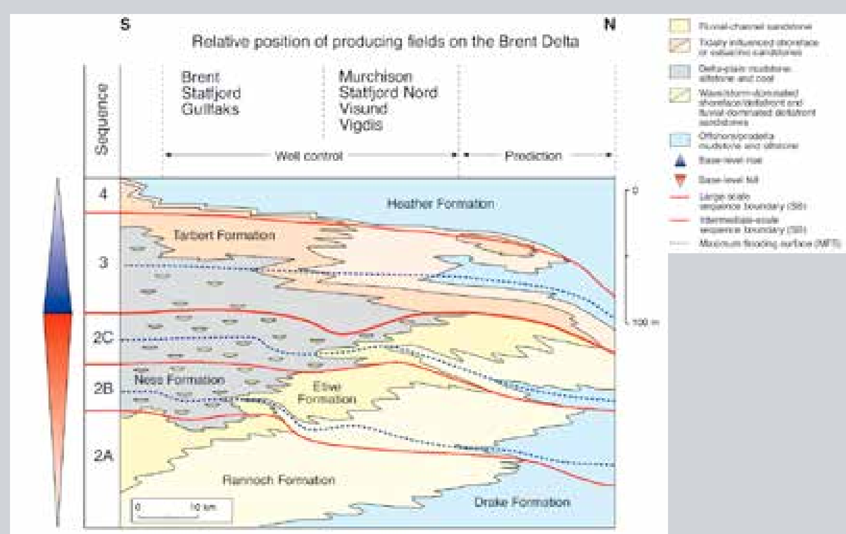
The Ness Fm (Bajocian to Bathonian) consists of an association of coals, mudstones, siltstones and fine to medium sandstones. Characteristic features are numerous rootlet horizons and a high carbonaceous content. The upper boundary is the change to the more massive and cleaner sandstones of the overlying Tarbert Fm. The formation is interpreted to represent delta plain or coastal plain deposition. The amount of silt and mudstones in the formation may act as a local seal. The Ness Fm shows large thickness variations ranging from 26 m up to about 140 m.

The Tarbert Fm (Bajocian to Bathonian) consists of grey to brown sandstones. The base of the formation is taken at the top of the last fining upward unit of the Ness Fm, either a coal-bearing shale or a coal bed. It is deposited in a marginal marine environment. Thickness in the type area varies between 14 and 45 m.

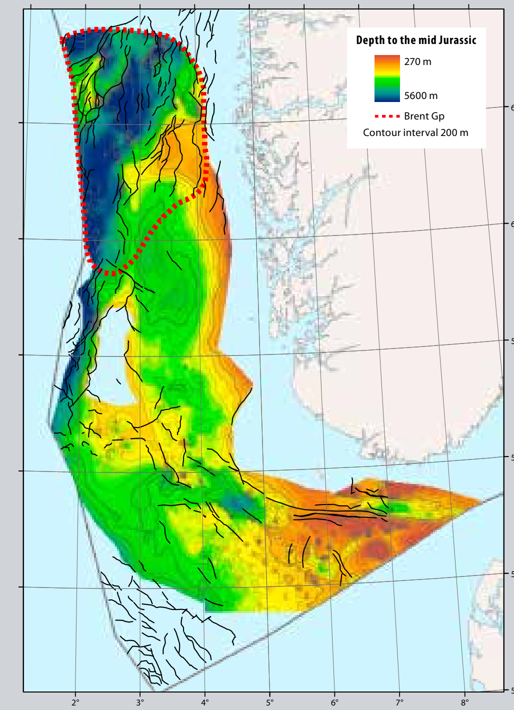
The Oseberg Fm (Upper Toarcian to Lower Bajocian) consists of relatively homogenous coarse-grained sandstones defined from the Oseberg Field (block 30/6) between the Viking Graben and the Horda Platform. The base of the formation is shales of the Dunlin Gp and the upper boundary is the micaceous sandstones of the Rannoch Fm. The formation has been correlated with various formations of the Brent Group, but whereas the Brent Group forms a deltaic unit building out from the south, the Oseberg Fm has its source area to the east. The thickness in the type area is between 20-60 m. The sandstones in the lower part are deposited in a shallow marine environment, overlain by alluvial sands and capped by sand reworked by waves.

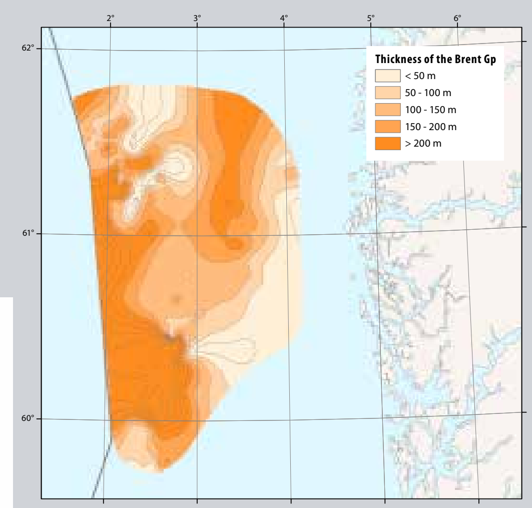
Burial depth of the Oseberg Fm varies between 2100 and 2800 m and porosities and permeabilities in the order of 23-26% and 250-2000 mD, respectively, are reported.

A time equivalent to the Brent Gp is the Vestland Gp which is defined in the southern part of the Norwegian North Sea.



Cross section through the Brent delta





Core photo well 30/6-7, 2679-2683 m (Ness Fm)

The Viking Group

Upper Middle Jurassic to Upper Jurassic / Lower Cretaceous (Bathonian to Ryazanian)

The Viking Gp has its type area in the northern North Sea north of 58^{o}N and east of the East Shetland Platform boundary fault. The Viking Gp is subdivided into five formations: the Heather, Draupne, Krossfjord, Fensfjord and the Sognefjord Fms. The lower boundary is marked by finer-grained sediments deposited over the sandy lithologies of the Brent and Vestland gps. In the northernmost area, where the Brent Gp is missing, the Viking Gp often sits unconformably on the Dunlin Gp. The upper boundary is, over most of the area, an unconformity overlain by low radioactive Cretaceous to Paleocene sediments.

The Heather and Draupne Fms are regionally defined and contain mainly silt and mudstones. The Draupne Fm in particular contains black mudstone with very high radioactivity due to high organic carbon content. The Krossfjord, Fensfjord and Sognefjord Fms represent more sandy facies and are restricted to the Horda Platform and northwards towards 62^{o}N.

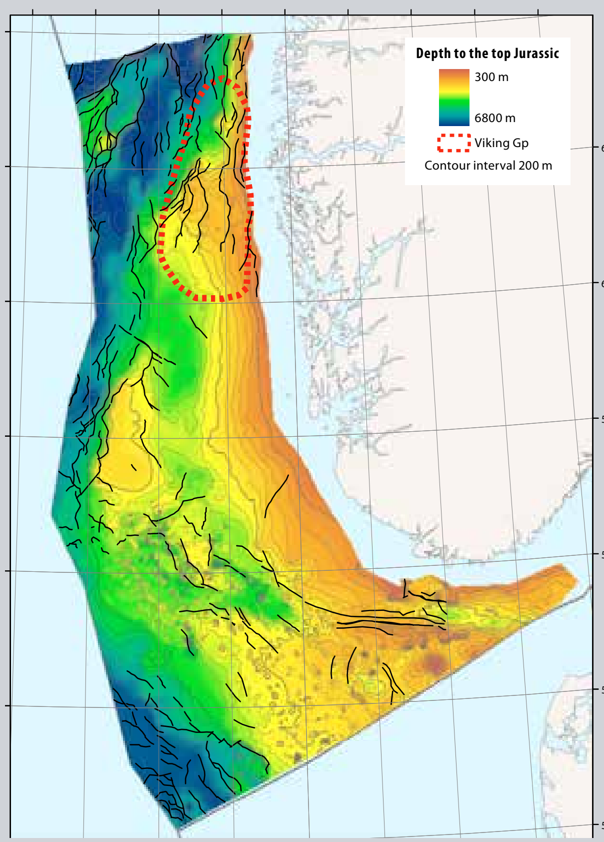
The thickness of the group varies considerably since the sediments were deposited on a series of tilted fault blocks, reflecting pre and syn-depositional fault activity and differential subsidence. The thicknesses in wells vary from a few meters up to 1039 m.

The Heather Fm (Upper Middle Jurassic to Upper Jurassic), overlying the Brent Gp sandy sequences, consists of mainly grey silty claystones, deposited in an open marine environment. The type well for the Heather Fm is well 211/21-1A (UK) and 33/9-1. The upper boundary is the radioactive and carbonaceous Draupne Fm.

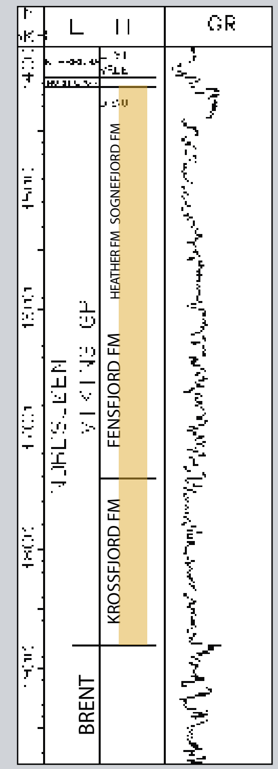
The Draupne Fm (Upper Jurassic/Lower Cretaceous) overlies the Heather Fm diachronically, and on the northern part of the Horda Platform, the formation overlies the sandstones of the Sognefjord Fm (type well 30/6-5). The Draupne Fm was deposited in a marine environment with restricted bottom circulation, often with anaerobic conditions. This led to the most prolific hydrocarbon source in the northern North Sea. Time-wise and environmentally, the Draupne Fm is equivalent to the UK Kimmeridge Clay Fm and the Tau Fm of the Norwegian-Danish Basin.

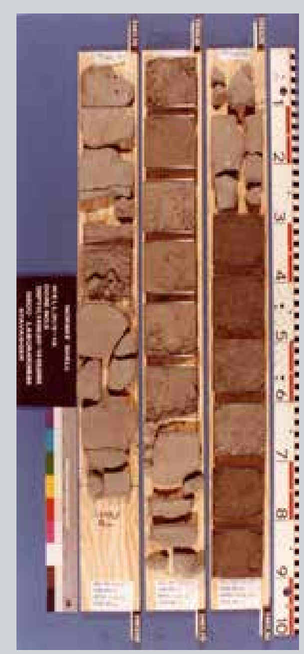
The Krossfjord Fm (Upper Middle Jurassic, Bathonian), the Fensfjord Fm (Upper Middle Jurassic, Callovian) and the Sognefjord Fm (Upper Jurassic, Oxfordian to Kimmeridgian) represent three coastal-shallow marine sands that interfinger with the Heather Fm on the gigantic Troll Field on the northern part of Horda Platform. The type well is 31/2-1. The total thickness of the three formations is in the order of 400-500 m. Each of the formations has been interpreted in terms of a "forestepping to backstepping" rift marginal wedge. This pattern has been interpreted as the response to eustatic sea-level changes or basin-wide changes in sediment supply, but also as a response to three separate rift events.

The burial depth varies from 1500-1600 m on the Horda Platform to more than 3500 m in the Sogn Graben. Porosities and permeabilities in the order of 19-34% and 1-1000 mD, respectively, have been reported from the Troll Field. The abundance of detrital mica in the sands is important in controlling the permeability.

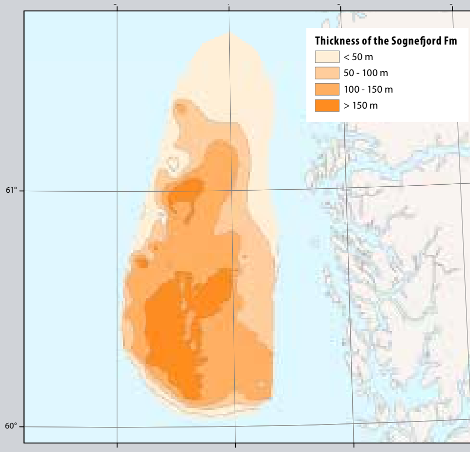


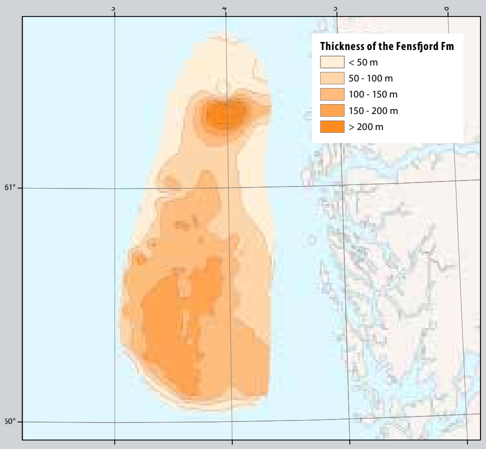
WELL LOG 31/2-1

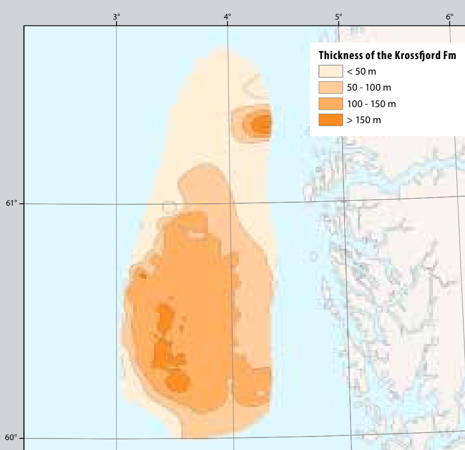




Core photo well 31/2-1R, 1459-1462 m (Sognefjord Fm)







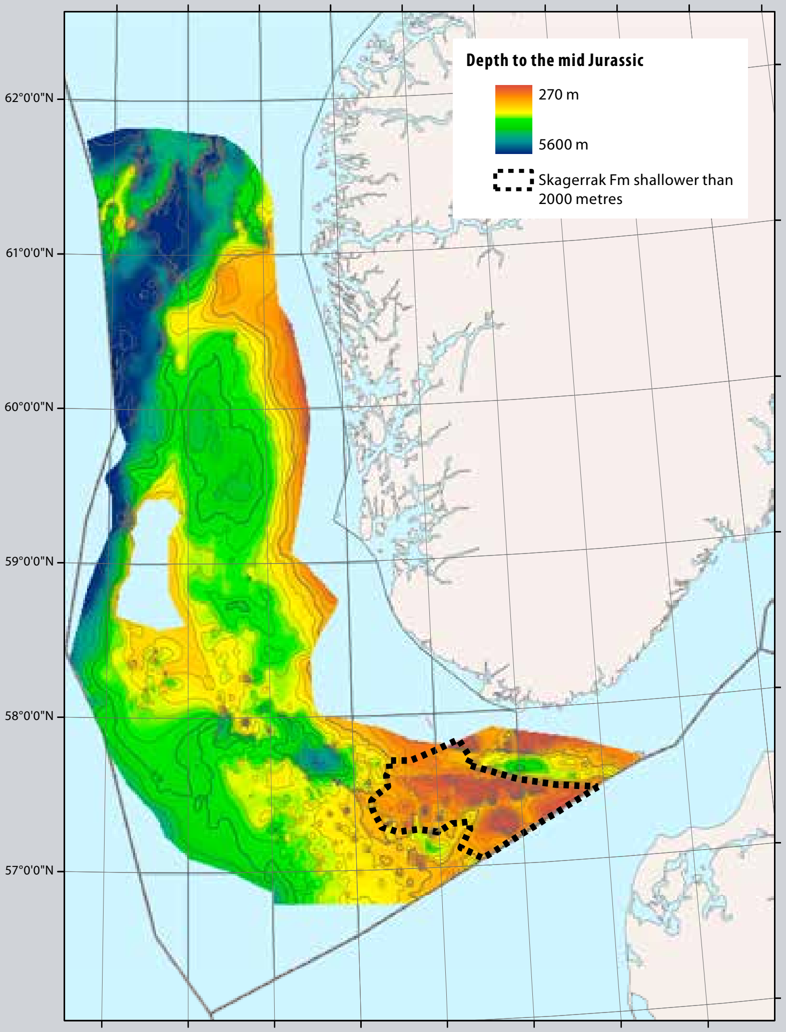
The Hegre Group - Skagerrak Formation

Middle to Upper Triassic

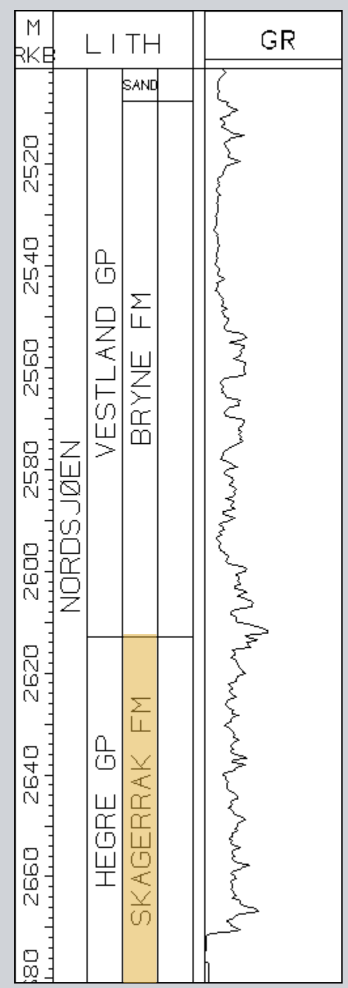
The Skagerrak Fm is present throughout the eastern part of the Central North Sea and the western Skagerrak, but may be missing over structural highs due to erosion and/or halokinesis. The type section is defined in well 10/8-1 in the eastern part of the Norwegian-Danish Basin. The base of the formation is sharp or gradational over claystones of the Smith Bank Fm. Over structural highs the formation may rest on pre-Triassic rocks. The upper boundary is normally an unconformity and overlain by Jurassic or younger sediments, but in a few wells it passes up into the Gassum Fm, a time equivalent to the Statfjord Gp of the northern North Sea.

The thickness in the type well is 1182 m, but based on seismic data a maximum thickness in excess of 3000 m is indicated further to the east. To the north-west and south-west, well control indicates a maximum thickness in the order of 660 and 250 m respectively.

The sediments were mainly deposited in alluvial fans and plains in a structurally controlled basin. Minor marine incursions are reflected by the local occurrence of glauconite in the uppermost part of the formation.
The burial depth of the formation in general exceeds 1500 m in western Skagerrak and more than 3000 m in the Egersund and Farsund basins. Porosity and permeability calculations shows mean values of 12.8% and <10 mD, respectively.



WELL LOG 9/4-3



Core photo well 15/6-7, 3414-3419 m

The Gassum and Fjerritslev Formations

Uppermost Triassic to Lower Jurassic
(Rhaetian in the west, Hettangian-Sinemurian in the northeast)

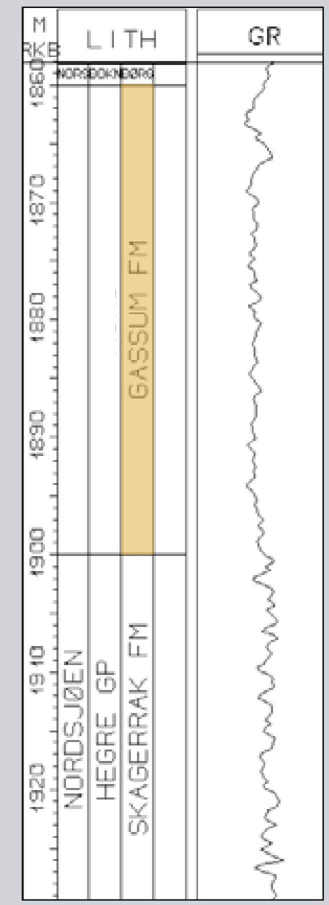
The Gassum Fm is defined from the Danish well No 1, and in the Norwegian-Danish Basin, well 17/10-1 is used as the reference well. The base of the formation is the Skagerrak Fm and the upper boundary is often the Lower Jurassic shales of the Fjerritslev Fm. In well 11/10-1 the Gassum Fm is overlain by marine silts and mudstones of the Boknfjord Gp forming a regional seal.

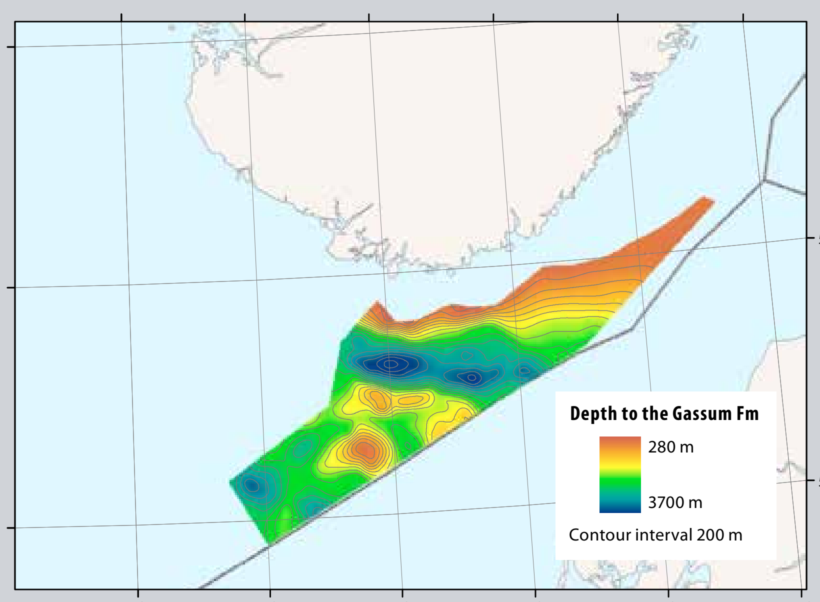
The formation is considered to occur throughout the Norwegian-Danish Basin, on the Sørvestlandet High and along the north-eastern margin of the Central Graben. In the Danish part of the basin, the thickness of the Gassum Fm varies from 50 m to more than 300 m northeast of the Fjerritslev Fault Complex. The distribution of the formation in the Norwegian part of the basin is more ambiguous because few wells have penetrated the unit. However, very often the wells are located on top or on the flanks of salt structures where the Gassum Fm most likely has been removed by erosion due to halokinesis and/or in relation to the mid-Jurassic erosional episode. Seismic profiles may indicate that the Gassum Fm is present in the Farsund Basin and sub-basins south of the Fjerritslev Fault Complex. Further to the west the formation is absent or below seismic resolution.

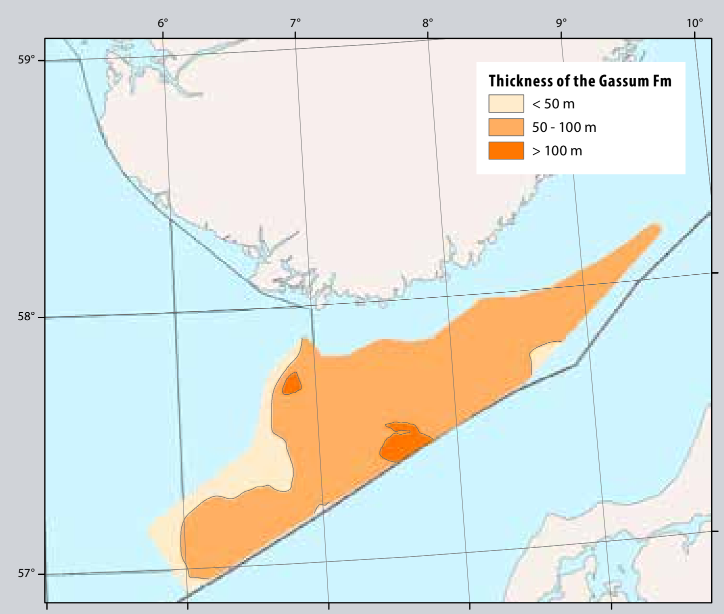
The formation represents deposition in fluvio-deltaic, deltaic and shoreface environments influenced by repeated sea level fluctuations. The mean burial depth exceeds 2000 m in the Norwegian part of the basin, but is less than 1500 m over structural highs, e.g. salt structures. Porosity and permeability calculations are based on Danish well data and show mean values of 20.3% and 400-500 mD, respectively. A time equivalent to the Gassum Fm is the Statfjord Gp in northern North Sea.

The Fjerritslev Fm is predominantly a silt and mudstone sequence. The type section of the formation is defined in the Fjerritslev-2 well. The lower boundary is defined at an abrupt change from sandy deposits of the Gassum and Skagerrak Fms to the claystones of the Fjerritslev Fm that may form a regional seal. The upper boundary is the overlying Middle to Upper Jurassic sandstones of the Haldager Fm. The formation is present over most of the Danish part of the Norwegian-Danish Basin. The thickness of the formation may exceed 1000 m locally, but is very variable due to basin relief, halokineses and mid-Jurassic erosion. In the Norwegian part of the basin the formation is discontinuous. However, similar to the Gassum Fm, seismic profiles reveal intervals, locally more than 300 m thick, which are thinning out or become truncated toward the flanks of salt structures. The formation represents deposition in a deep offshore to lower shoreface environment.

WELL LOG 11/10 1







The Vestland Group

Middle Jurassic to Upper Jurassic
(Bajocian to Volgian)

The Vestland Gp is divided into five formations: The Sleipner, Hugin, Bryne, Sandnes and Ula Fms.

The lower boundary is the Lower Jurassic mudstones of the Dunlin Gp or the Fjerritslev Fm and the upper boundary is defined by the incoming of mudstone-dominated sequences: The Viking Gp in the Southern Viking Graben, the Tyne Gp in the Central Graben and the Boknfjord Gp in the Norwegian-Danish Basin. These mudstone-dominated groups are important as regional seals.

The Vestland Gp is widely distributed in the southern part of the Norwegian Sea. The Sleipner and Hugin fms are defined from the Southern Viking Graben fringing the Utsira High. The Bryne Fm is defined from the Central Graben and the Norwegian-Danish Basin, the Sandnes Fm from the Norwegian Danish Basin and the Ula Fm from the western margin of the Sørvestlandet High. The thickness of the group varies considerably, from 123 to more than 450 m reported from wells. Seismic mapping indicate greater thicknesses in syn-sedimentary fault-bounded sub-basins related to halokinesis. On structural highs the group or part of the group may be missing due to erosion.

The depositional environment varies from deltaic coal-bearing, silt and shale sequences at the base with more marine-influenced sands in deeper parts of the basin. The upper part of the group consists mainly of fairly clean marine sands.

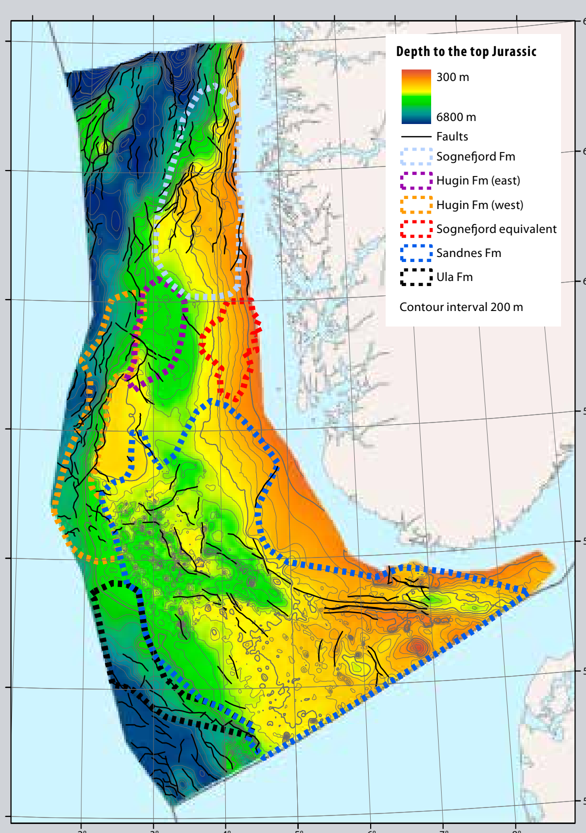
The Sleipner Fm is defined in the southern Viking Graben between approximately 580 and 600N, in a fluvio-deltaic coaly setting. The Fm is broadly equivalent to the Ness Fm of the Brent Gp in the East Shetland Basin. Thickness in the type area varies between 40 and 50 m. Non-marine sands of equivalent age in the Central Graben and Norwegian-Danish Basin are referred to as the Bryne Fm.

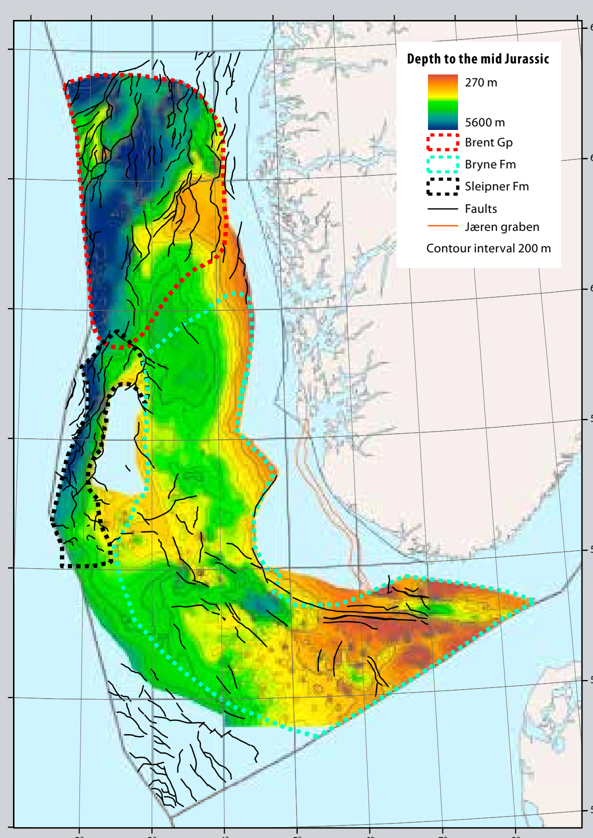
The Hugin Fm, overlying the Sleipner Fm, represents mainly a near-shore, shallow marine sandstone. The Fm is located in the southern Viking Graben in the northern part of the Sørvestlandet High. The upper boundary of the formation represents a transition into silt and mudstones of the Viking Gp. Thicknesses, according to wells in the type area, are in the order of 50 to 170 m.

The Bryne Fm is defined from the Norwegian-Danish Basin and Central Graben, representing a fluvial/deltaic environment. The base of the Fm is the partly eroded shales of the Fjerritslev Fm or Triassic sandy rocks. The top is defined by siltstones and mudstones of the Boknfjord Gp, forming a regional seal.

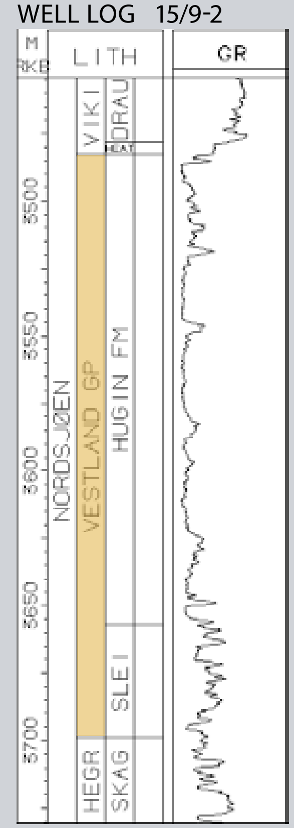
The Sandnes Fm is defined from the northern part of the Åsta Graben and Egersund Basin representing a coastal/shallow marine environment. The contact with the underlying Bryne Fm or older rocks is usually an unconformity and it is overlain by siltstones and mudstones of the Boknfjord Gp.

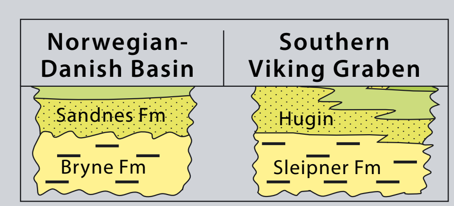
The Ula Fm is defined around the eastern highs flanking the Central Graben and represents a shallow marine deposit. The base of the Fm is towards the non-marine Bryne Fm, and the top is where the marine sands are overlain by the silts and mudstones of the Tyne Gp.





WELL LOG 15/9-2





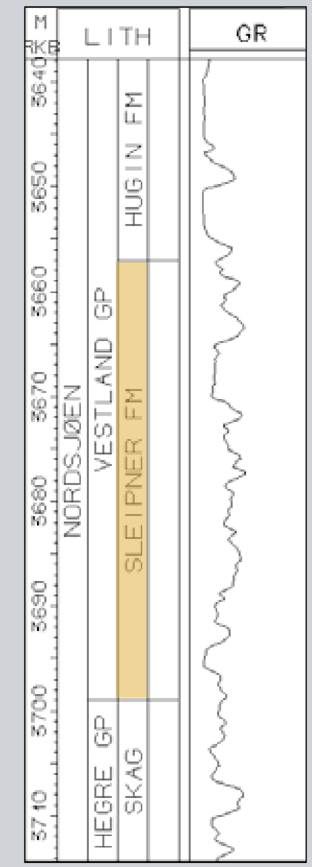
The Vestland Group - Sleipner Formation

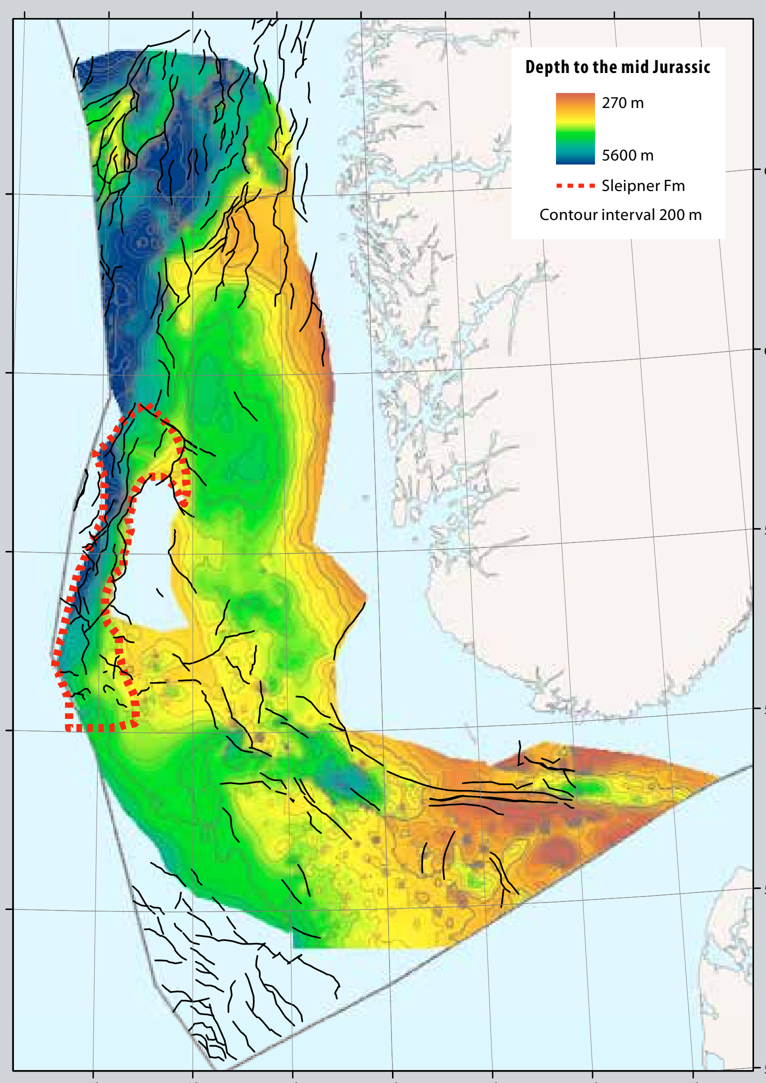
Middle Jurassic (Bajocian to Early Callovian)

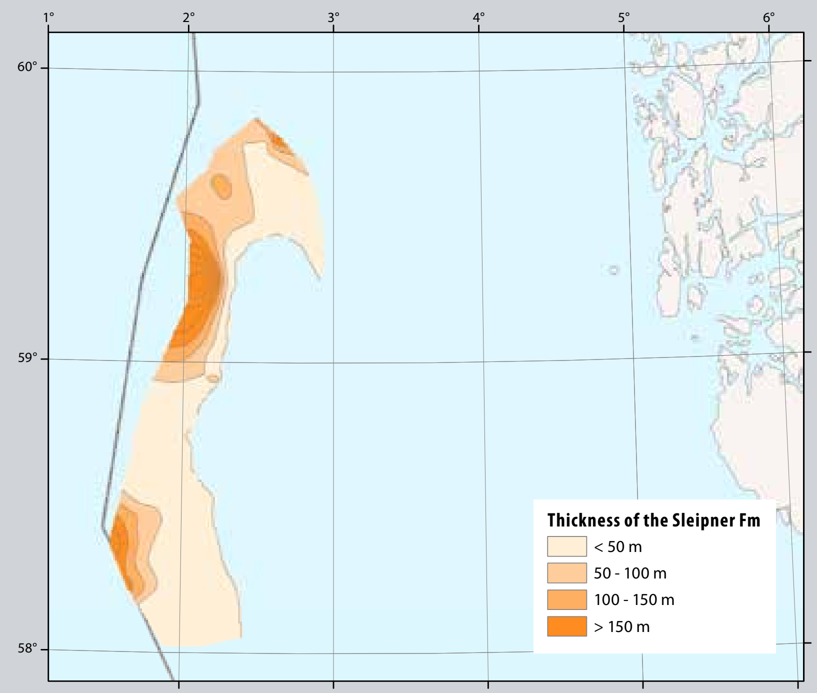
The Sleipner Fm is defined at the base of the Vestland Gp in the southern Viking Graben. The formation lies unconformably over Lower Jurassic and older rocks. The upper boundary in the type well (15/9-2) is the sands of the Hugin Fm, but the formation can also be overlain by shales of the Viking Gp.

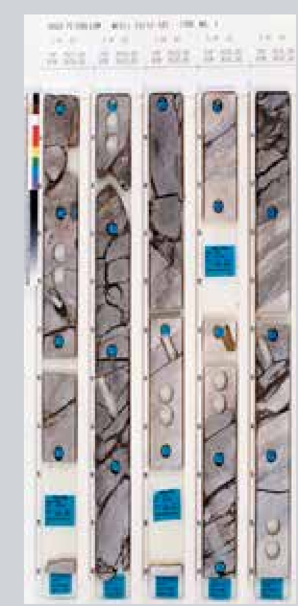
The Sleipner Fm is found in the southern Viking Graben between approximately 580 and 600N, and is broadly equivalent to the Ness Fm of the Brent Gp in the northern North Sea. The name Sleipner Fm should be applied when the marine sandstones underlying the coal-bearing sequence is missing. Non-marine sands of equivalent age in the Central Graben and the Norwegian-Danish Basin are defined as the Bryne Fm. Thickness in the type area varies between 40 and 50 m. The Sleipner Fm represents a continental fluvio-deltaic coal-bearing sequence. Burial depth of the formation over the Sleipner West Field is approximately 3400 m and average porosities and permeabilities of 16-20% and 0.1-4000 mD, respectively, are reported.

WELL LOG 15/9-2









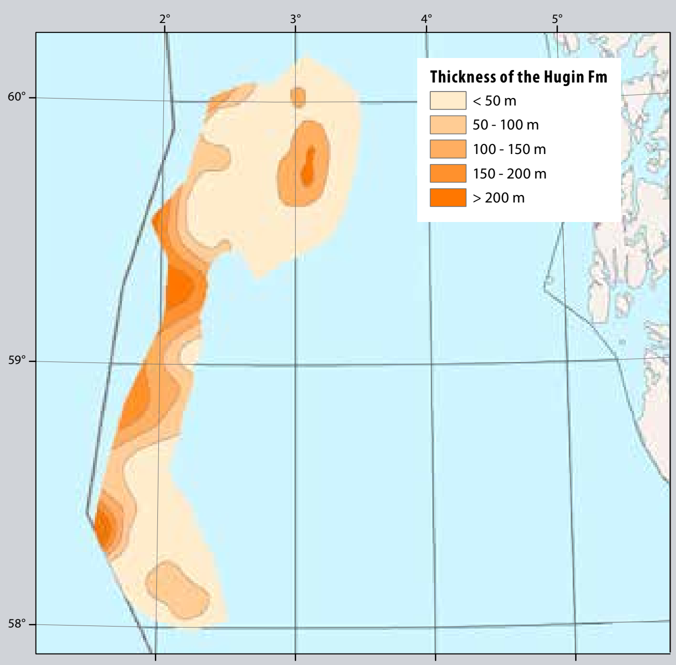
Core photo well 15/12-10 S, 3427-3432 m

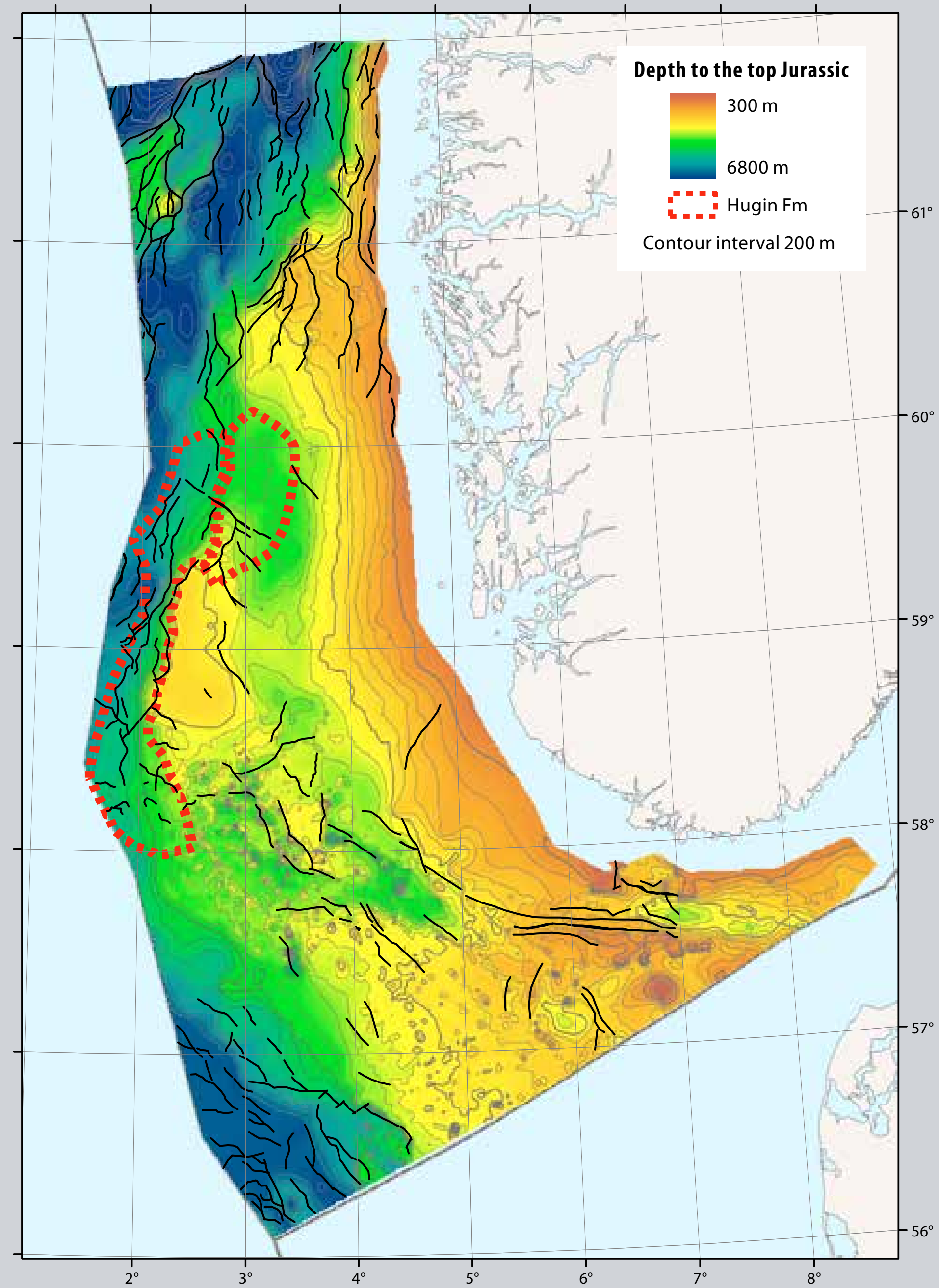
The Vestland Group - Hugin Formation

Middle Jurassic to Upper Jurassic
(Lower Bathonian to Lower Oxfordian)

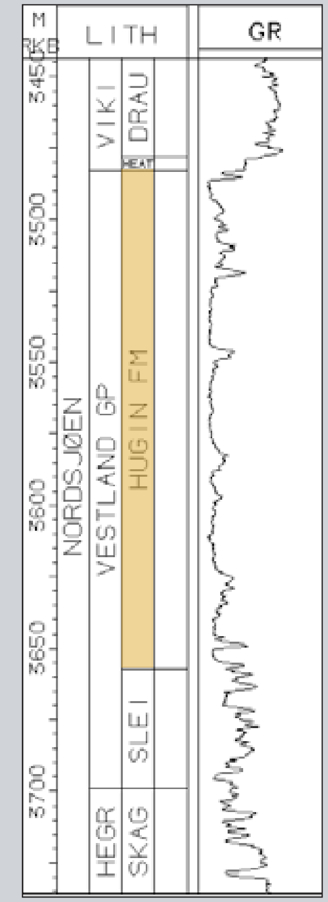
The Hugin Fm is found in the southern Viking Graben in the northwestern part of the Sørvestlandet High, where it overlies the deltaic coal-bearing Sleipner Fm. The upper boundary is the shales of the Viking Gp.

Thickness in the type well 15/9-2 is 174 m. Generally the thickness decreases to the east and north. The thickness distribution of the Hugin Fm is partly controlled by salt tectonics. The depositional environment is interpreted in terms of a near-shore, shallow marine environment with some continental fluvio-deltaic influence. Burial depth of the formation over the Sleipner West Field is approximately 3400 m and reported average porosities and permeabilities is in the range between16-20% and 0.1-4000 mD, respectively.





WELL LOG 15/9-2



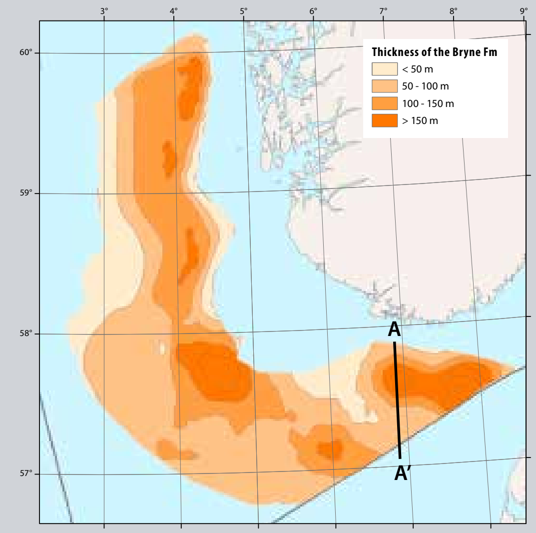
Core photo well 25/2-15R2, 3574-3579 m

The Vestland Group - Bryne Formation

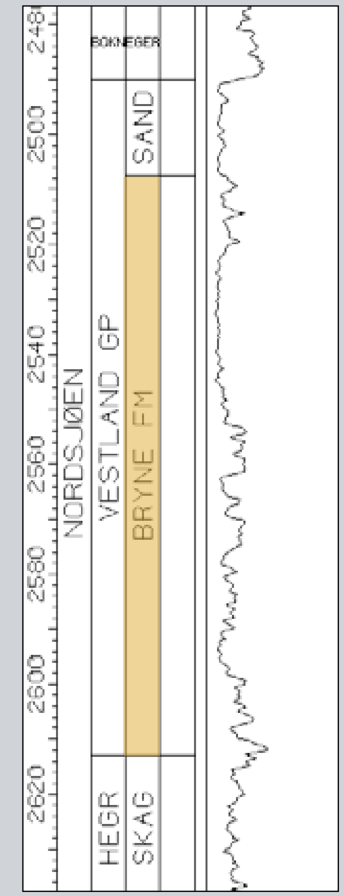
Middle Jurassic (Bajocian to Early Callovian)

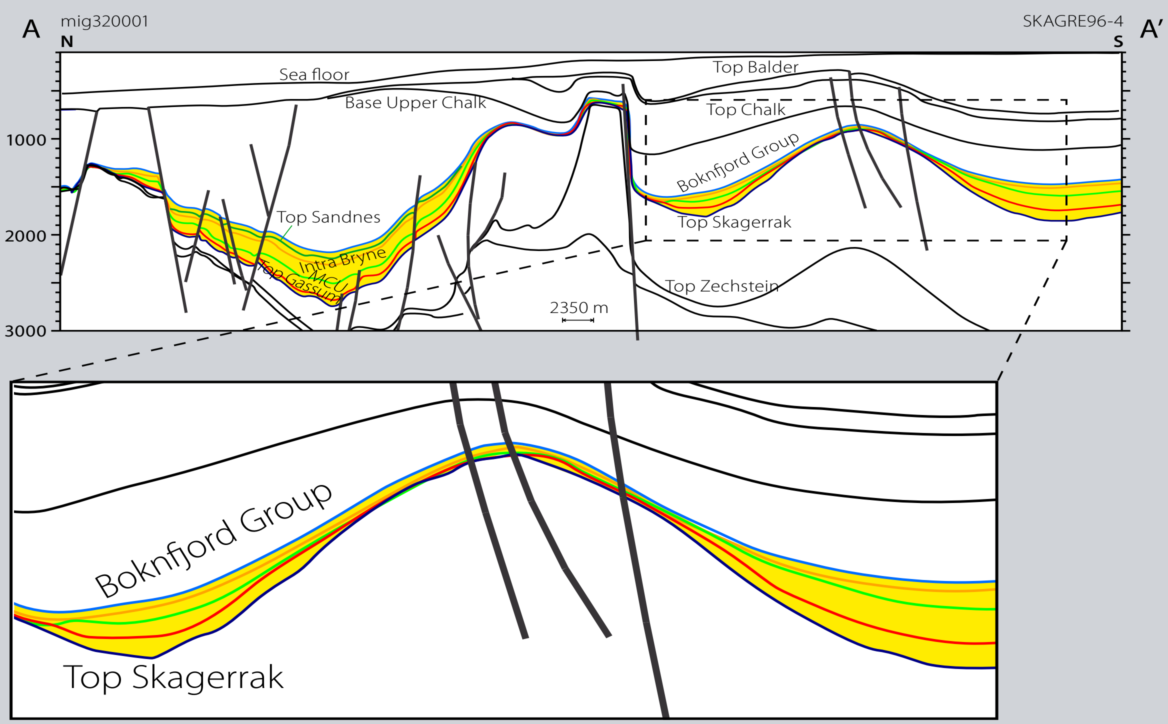
The Bryne Fm forms the base of the Vestland Gp in the Norwegian-Danish Basin and in the Central Gaben. The lower boundary represents an unconformity, with partly eroded shales of the Fjerritslev Fm or with Triassic rocks below. The upper boundary is siltstones and mudstones of the Boknfjord Gp that could form a regional seal. The type section for the formation is defined in well 9/4-3 with a thickness of 106 m. The formation is thin and patchy in western Skagerrak, but the seismic indicates thicknesses of several hundred meters in syn-sedimentary fault-bounded sub-basins, e.g. Egersund and Farsund Basins, and local depocentres south of the Fjerritslev Fault Zone.

The Bryne Fm reflects deposition in fluvial, deltaic and lacustrine environments. Shallow marine environments may in periods have prevailed in the fault-controlled sub-basins. The burial depth is in general more than 1500 m, except over structural highs where it may be less than 1000 m. In the Egersund Basin the burial depth exceeds 3000 m. Porosity and permeability calculations show mean values of 20.4% and 100-200 mD, respectively. The formation corresponds to the Haldager Fm in the Danish part of the Norwegian-Danish Basin.

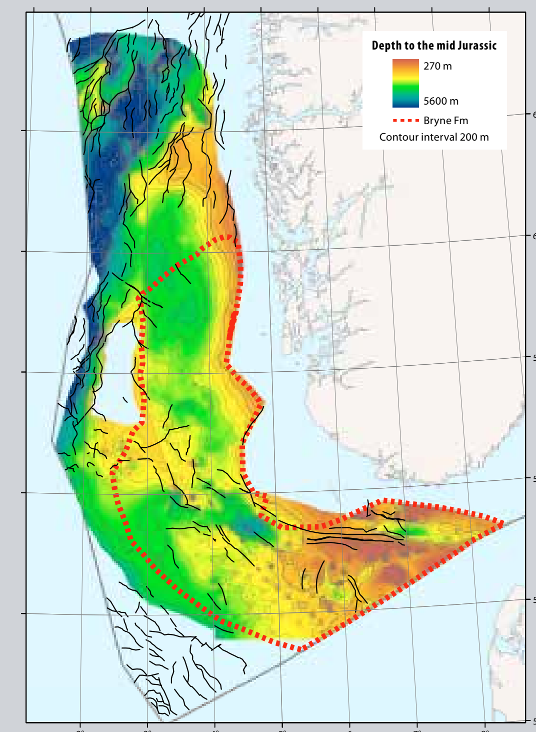


WELL LOG 9/4-3





The enlarged rectangle shows the Jurassic section within a salt-induced structure. MCU is the base of the Bryne Formation.



Core photo well 3/7-4, 3479-3483 m

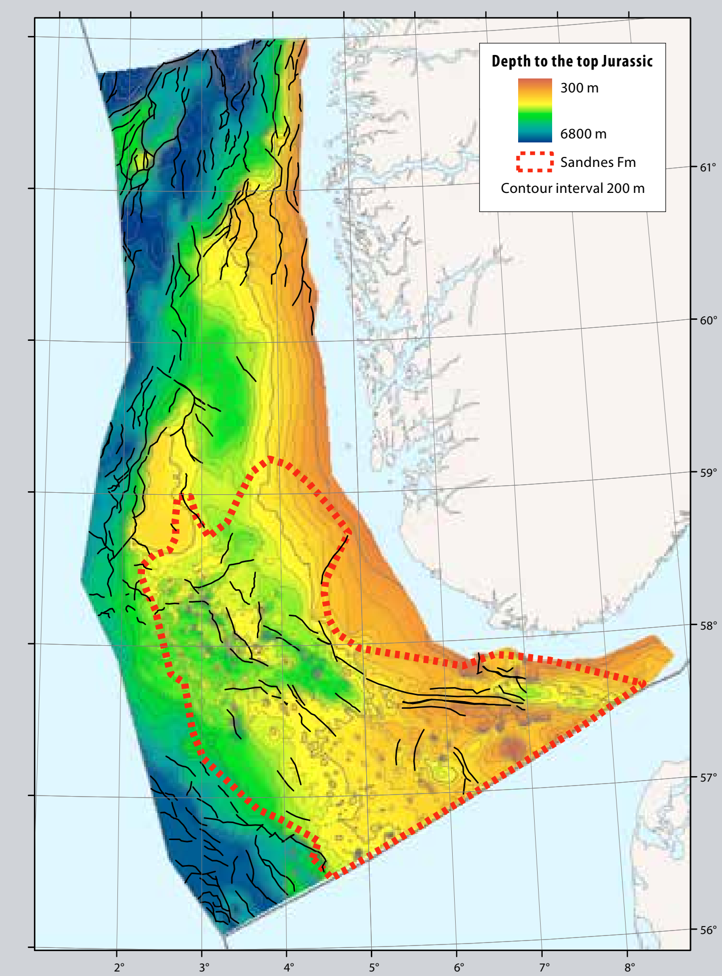
The Vestland Group - Sandnes Formation

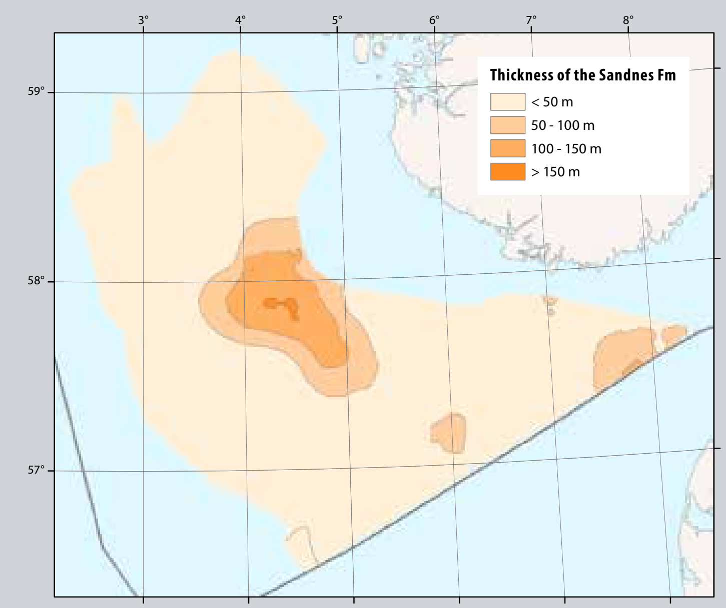
Middle Jurassic to Upper Jurassic
(Upper Callovian to Lower Oxfordian)

The Sandnes Fm is defined from the Norwegian-Danish Basin. The lower boundary, the non-marine Bryne Fm or older rocks, is commonly defined at the base of massive and clean sand. The upper boundary is the marine silts and mudstones of the Boknfjord Gp, which could form a regional seal. The type section for the formation is well 9/4-3.

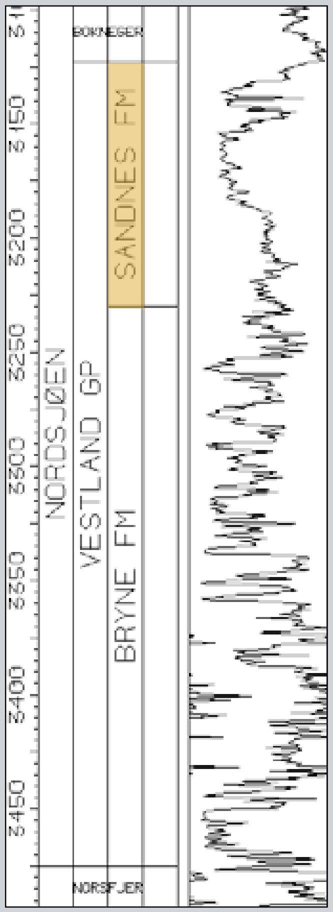
The formation is developed in the southern part of the Åsta Basin and the Egersund Basin. Based on seismic mapping and well data in the Egersund Basin, the thickness exceeds 100 m in large areas. Similar thicknesses may be reached in local depocentres, elsewhere the thickness is less than 50 m. Where the Sandnes Fm is thick, the lower part may represent a distal facies that is time equivalent to the uppermost part of the Bryne Fm. The Sandnes Fm mainly reflects deposition in a shallow marine (e.g. shoreface) to offshore environment. The burial depth is in general more than 1500 m except over structural highs where it may be less than 1000 m. In the Egersund and Farsund basins and the south-western part of the Åsta Graben the burial depth exceeds 2500 m. Porosity and permeability calculations show mean values of 23.0% and 400-500 mD, respectively.

The formation is broadly comparable in lithofacies and depositional environments with the Hugin Fm in the southern Viking Graben.





WELL LOG 9/2-2



Core photo well 3/7-4, 3452-3457 m

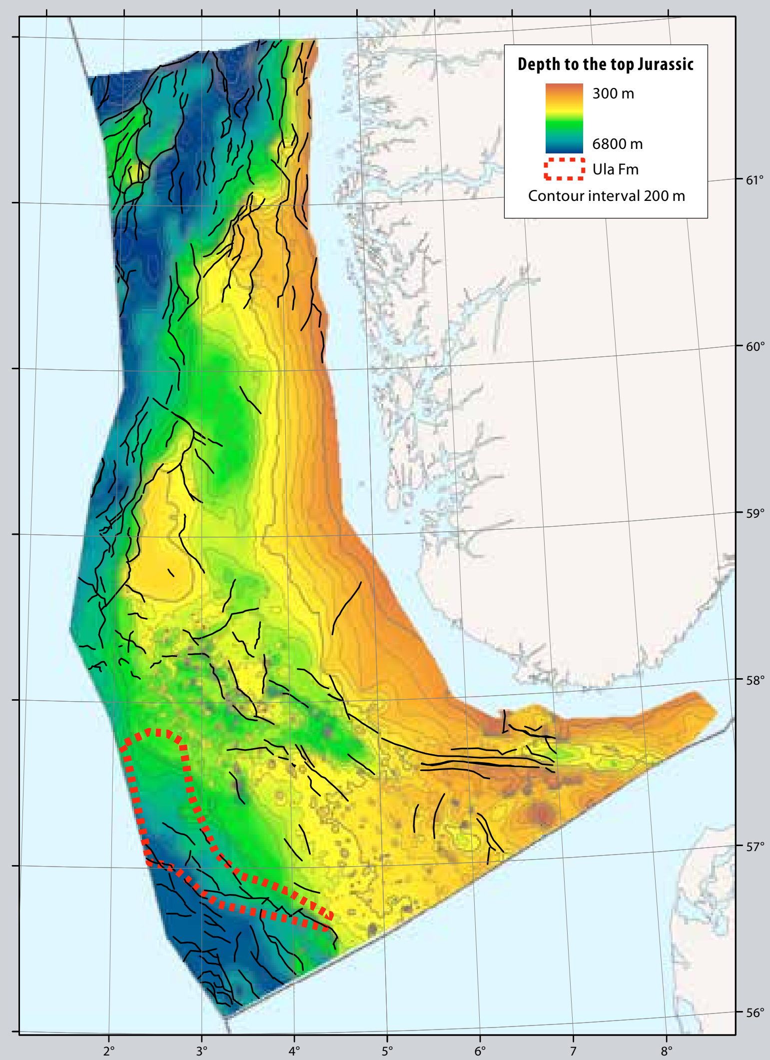
The Vestland Group - Ula Formation

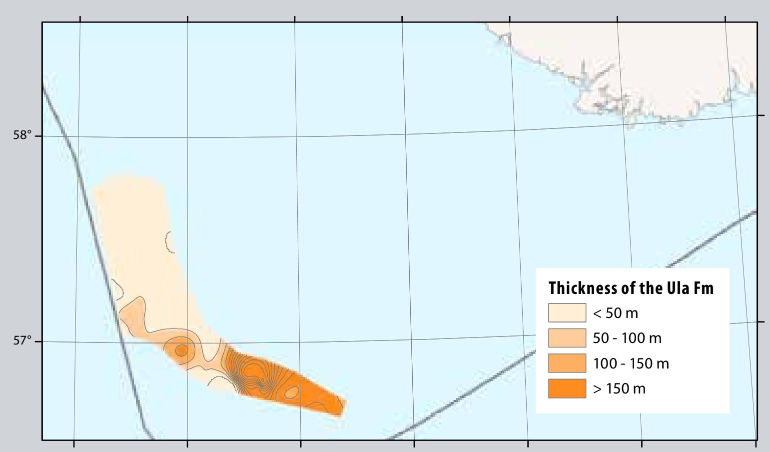
Upper Jurassic-Lower Cretaceous
(Oxfordian- Ryazanian)

The Ula Fm is defined from the western boundary of the Sørvestlandet High from the Ula Field. The base of the formation is the non-marine Bryne Fm and the top is the marine siltstones and mudstones of the Tyne Gp, forming a regional seal. The Ula Fm is defined around the eastern flanking highs of the Central Graben, in particular on the south-west flank of the Sørvestlandet High, and moving towards the basin, i.e. to the west, into marine shale. In the type well 7/12-2 the thickness is 152 m. It thins rapidly towards the east, but can be followed along the NW-SE structural grain controlled by halokinesis. The sands of the Ula Fm are generally deposited in a shallow marine environment.

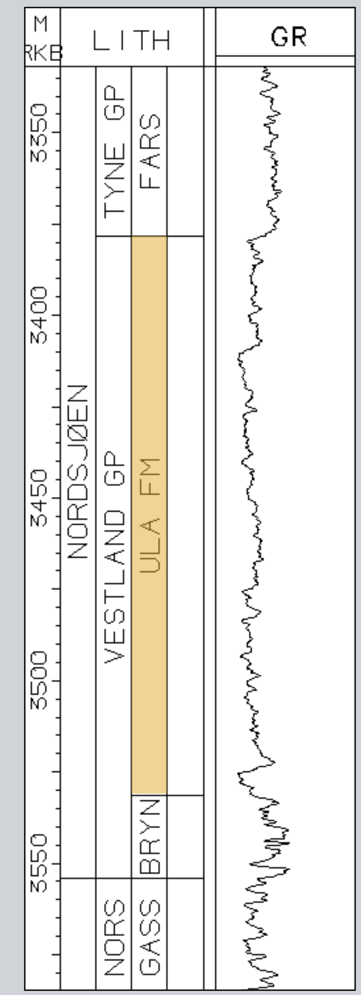
In the type area, the Ula Fm is buried to a depth of more than 3000 m. In the Ula Field, the crest of the structure is 3345 m and porosities and permeabilities are reported in the range 15-22% and 0.2-2800 mD, respectively.

The Ula Fm has similarities both in lithofacies and partly in age with the Hugin Fm in the southern Viking Graben (Sleipner area) and the Sandnes Fm in the Norwegian-Danish Basin.





WELL LOG **7/12-2**



Core photo well 2/12-1, 4648-4653 m

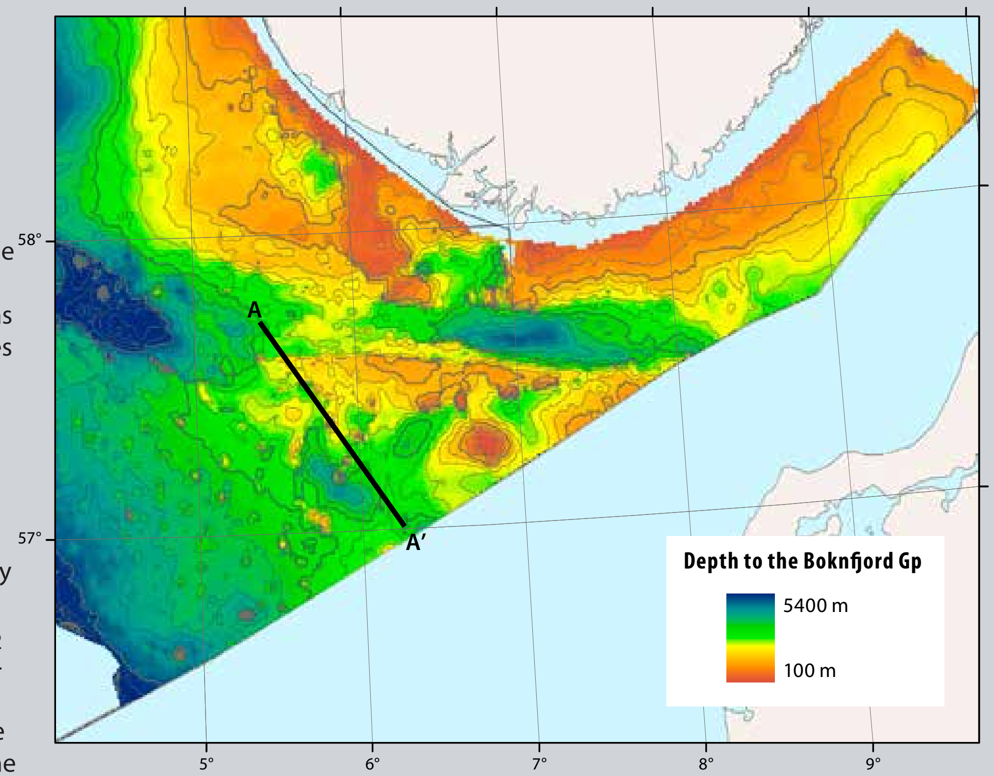
The Boknfjord Group

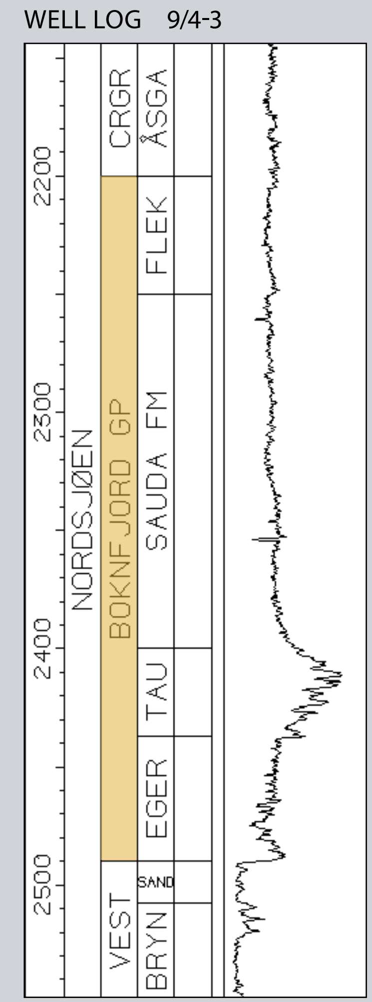
Middle Jurassic to Upper Jurassic
(Callovian to Ryazanian)

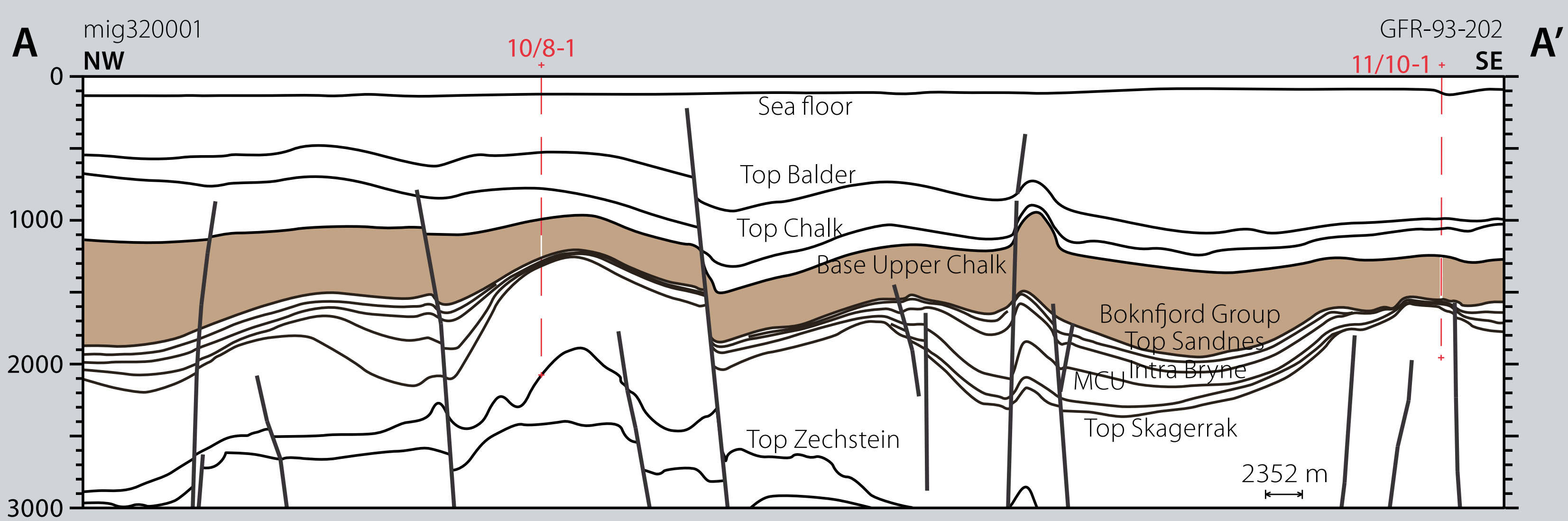
The Boknfjord Gp is defined from the Fiskebank and Egersund Basin and the type well is well 9/4-3. The Boknfjord Gp is dominated by shales and is considered as the primary seal for the underlying potential CO_2 aquifers. The group is subdivided into four formations: The Egersund (base), Tau, Sauda and Flekkefjord Fms. As all of the formations have seal properties, they will be treated as one composite seal. The lower boundary is the sandstones of the Sandnes or Bryne formations. The upper boundary is the Cromer Knoll Gp dominated by claystones.

The Boknfjord Gp is present in the Norwegian part of the Norwegian-Danish Basin. Well data show that the group in general is more than 100 m thick in western Skagerrak, and in the Egersund Basin up to 500 m thick. The upper boundary is the Cromer Knoll Gp dominated by mudstones with a varying content of calcareous material. It forms a secondary seal for the underlying potential CO_2 aquifers. The Boknfjord and Cromer Knoll Gp form a combined seal which can be mapped seismically. The seal is in general several hundred metres thick and may be more than 2000 m thick in the Egersund and Farsund Basins. The sealing package is locally truncated by salt diapirs, as seen in well 11/9-1.

The sediments of the Boknfjord Group were mainly deposited in open marine, low energy basin environments.







The Rogaland Group

Paleocene-Lower Eocene

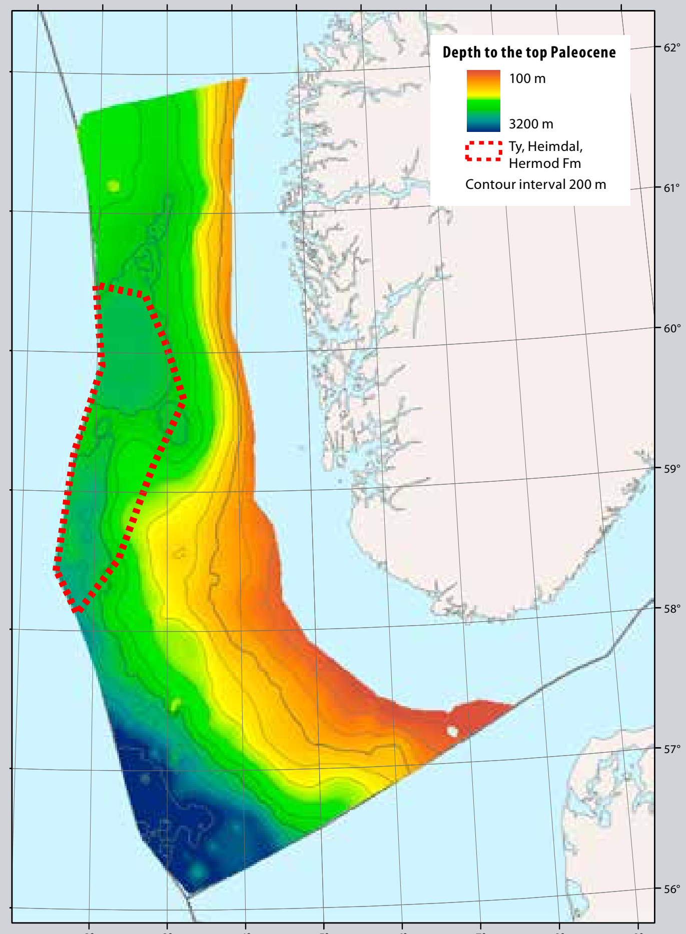
The Rogaland Gp is subdivided into twelve formations. This description will focus on possible aquifers. In general the sequences start off from the west as more proximal and interfinger with more distal sediments to the east. The group is widely developed in the northern and central North Sea. The base of the group is the contact with underlying chalk or marl sequences of the Shetland Gp. The upper boundary is the change from laminated tuffaceous shales (Balder Fm) to sediments of the Hordaland Gp.

The Rogaland Gp is thickest in the west in the UK sector (about 700 m), thinning eastwards and southwards with recorded well thicknesses in the order of 100 m. Depositionally, the Rogaland Gp represents submarine fan / gravity flow sediments transported into deeper water. The sand-bodies are generally lobe shaped and pass laterally into silt and mudstones to the east.

The Ty Fm (Lower Paleocene) was deposited from the Shetland Platform as a deep marine fan and has been identified in the southern Viking Graben in the north-western part of quadrant 25, and northern part of quadrant 15. The formation consists mainly of clean sandstones with a thickness in well 15/3-1 of 159 m. The lower boundary is calcareous rocks of the Shetland Gp, and the upper boundary is transitional to the shales of the Lista Fm, but also against the sands of the Heimdal Fm. The formation may also interfinger with the Våle Fm to the east.

The Heimdal Fm (Paleocene) was deposited as a submarine fan sourced from shallow marine sands on the East Shetland Platform. It is identified in the western parts of quadrant 30, most of quadrant 25 and 15 and as cleaner sand in the south-eastern part of quadrant 15 into the north-western part of quadrant 16 (Meile Mbr (informal)). The thickness of the Heimdal Fm is 356 m in the type well (25/4-1) and 236 m in well 15/9-5. It thins rapidly east of these wells and south of well 15/9-5. The base is usually the transition from the shales of the Lista Fm, but also sandstones of the Ty Fm. The upper boundary is usually a transition from the Heimdal sandstones into the shales of the Lista Fm. Locally it is overlain by the sands of the Hermod Fm.

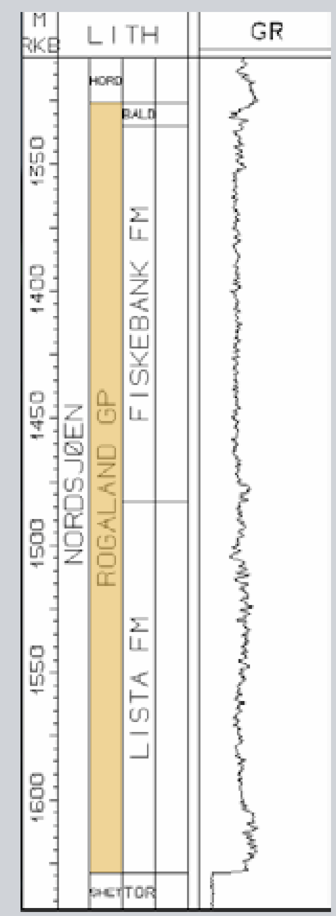
The Hermod Fm (Upper Paleocene) consists of mainly fine-grained sandstones deposited in a submarine fan setting connected to the deltaic Moray Gp in the UK sector. The formation is located mainly in the South Viking Graben in the north-western part of quadrant 25 and extends into the southern part of quadrant 30. The thickness of the formation is 140 m in the type well 25/2-6 and it thickens toward the central part of the distribution area. The lower boundary of Hermod Fm is usually a transition to silts and mudstones of the Lista Fm or the Sele Fm. It may also rest directly on the more varied sandstones of the Heimdal Fm. The upper boundary of the Hermod Fm is sharp against the dark silt and mudrocks of the time-equivalent Sele Fm.



The Fiskebank Fm (Upper Paleocene) has been identified from the Norwegian-Danish Basin and in the type well, 9/11-1, with a thickness of 148 m. The lower boundary is silt and mudstones of the Lista Fm and the upper boundary is tuffaceous shales of the Balder Fm. The formation is developed mainly in the Åsta Graben in the Norwegian-Danish Graben. The thickness in wells varies between 26 to 148 m. The Fiskebank Fm probably represents basin margin deposits and appears to be mostly time equivalent with the Sele Fm.

The Balder Fm (Paleocene to Upper Eocene) consists of vari-coloured laminated shales, interbedded with sandy tuffs and distributed over much of the North Sea. The thickness varies between less than 20 m to more than 100 m. The Balder Fm was deposited in a deep marine environment and the tuffaceous material probably came from more than one volcanic source. The lower boundary of the Sele or Lista fms is marked by the incoming of tuffaceous material. The upper boundary is defined at the transition from the laminated Balder Fm to the non-laminated, often glauconitic and reddish overlying sediments of the Hordaland Gp.

WELL LOG 9/11-1



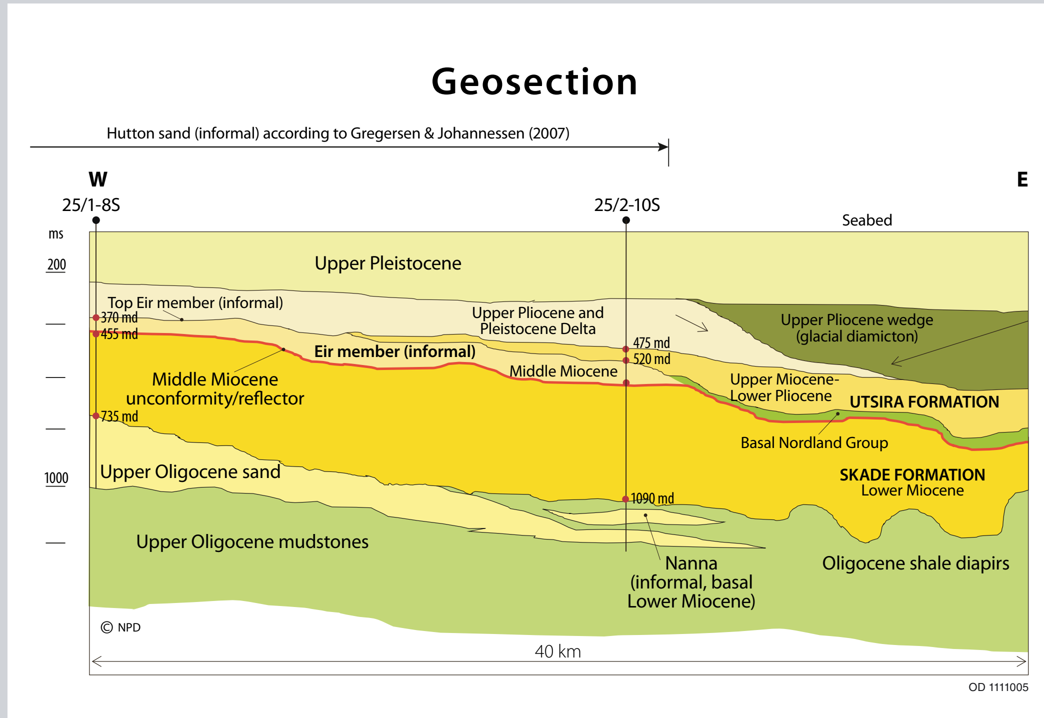
The Hordaland Group - Skade Formation

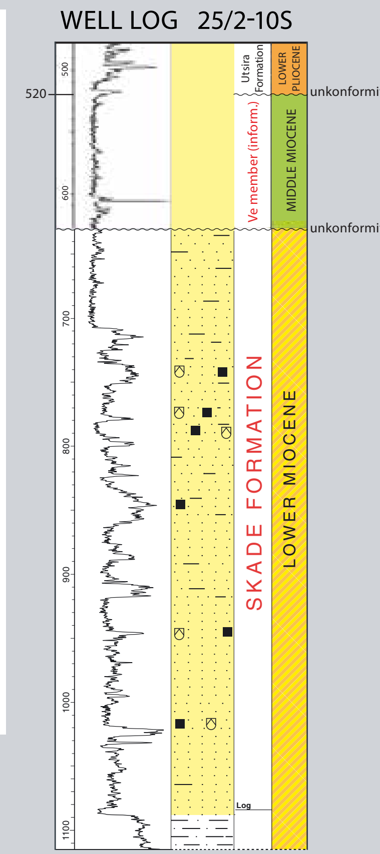
Eocene to Middle Miocene

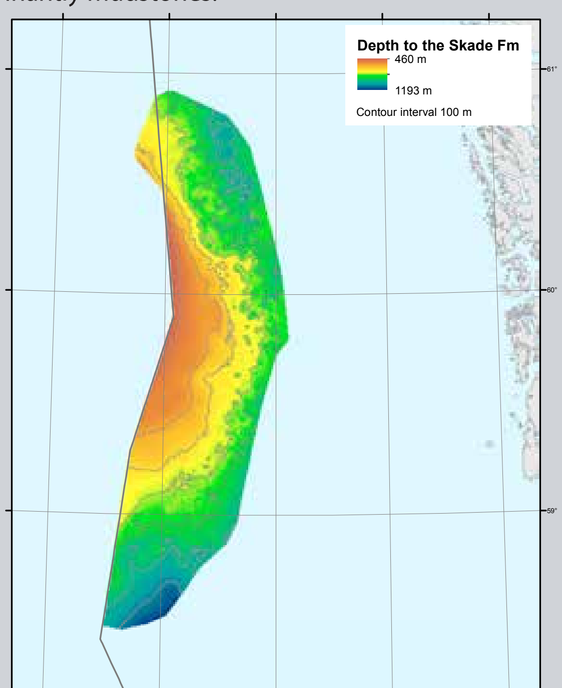
The Skade Formation of the Hordaland Group together with the Eir (informal) and Utsira Formations and the Upper Pliocene sands of the Nordland Group form the outer part of a large deltaic system with its source area on the East Shetland Platform. The proximal parts of this system are mainly located in the UK sector, and these deposits are named the Hutton sand (informal). In the Norwegian sector, sands belonging to the system are the Miocene–Lower Pliocene Skade, Eir (informal) and Utsira Fm, and Upper Pliocene sands of the Nordland Group (no formal name).

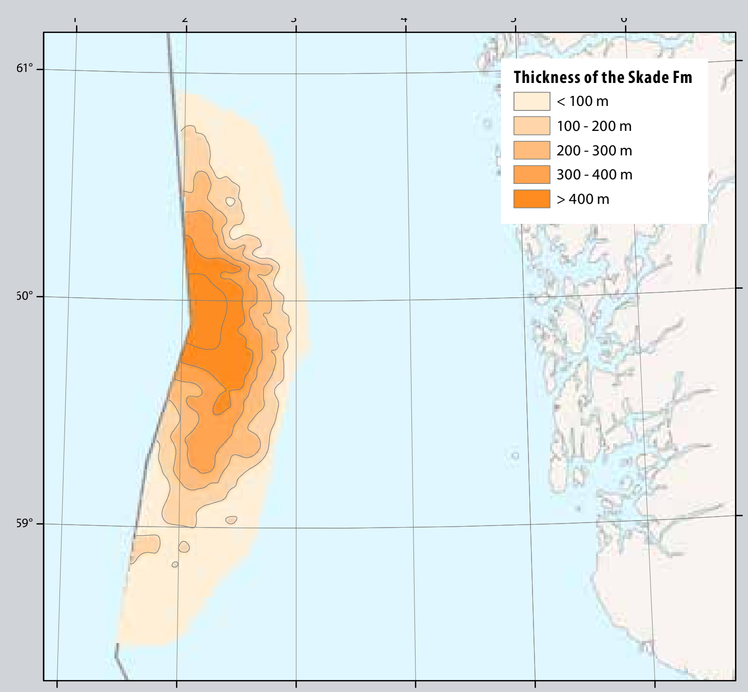
The Skade Fm, Lower Miocene, consists of marine sandstones (mainly turbidites) deposited over a large area of the Viking Graben (from 16/1-4 in the south to 30/5-2 in the north). The maximum thickness exceeds 300m and decreases rapidly towards the east, where the sands shale out or terminate towards large shale diapirs.

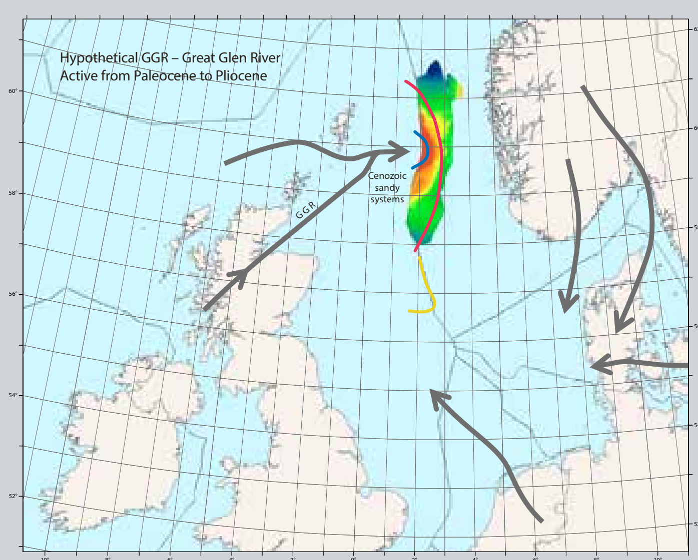
The Eir Fm (informal), Middle Miocene, is recorded in several wells in the Viking Graben, including 15/9-13 in the south-east and 25/2-10S and 30/6-3 further north. The thickness map shows the distribution of the northern part of the formation. In the southern part of the deltaic system, the sand is generally shaling out closer to the UK/Norway boundary line. The Eir Fm (informal) overlies the mid Miocene unconformity and forms the base of the Nordland Gp. Elsewhere in the North Sea the Middle Miocene is dominantly mudstones.











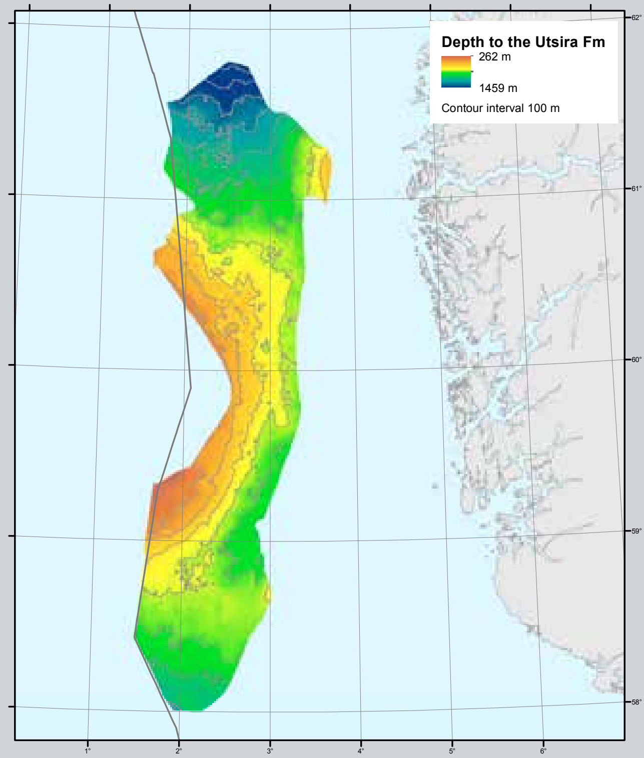
Suggested drainage patterns for Miocene deposits in the North Sea area. Drainage through the Great Glen trend in Scotland has not been documented.

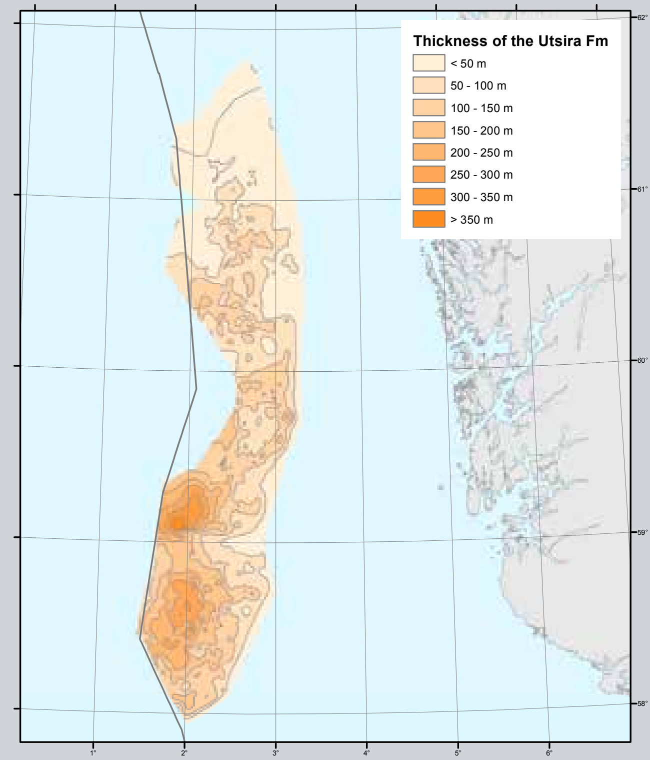
The Nordland Group - Utsira Formation

Uppermost Middle Miocene to Quaternary

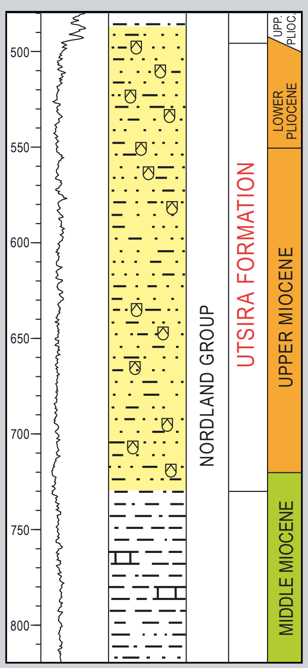
The Utsira Fm of the Nordland Group (uppermost Middle Miocene to Quaternary) consists of marine sandstones with source area mainly to the west. The maximum thickness exceeds 300 m. The sands of the Utsira Fm display a complex architecture and the elongated sand body extends some 450 km N-S and 90 km E-W. The northern and southern parts consist mainly of large mounded sand systems. In the middle part the deposits are thinner, and in the northernmost part (Tampen area) they consist of thin beds of glauconitic sands.

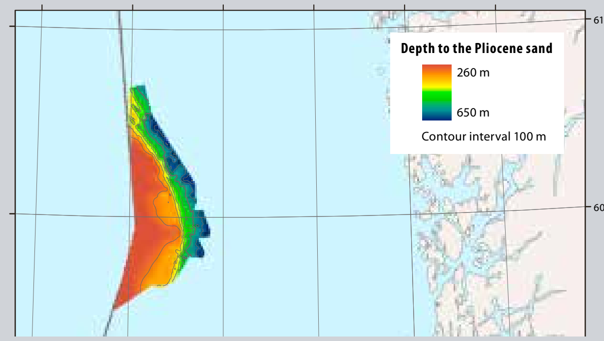
Upper Pliocene deltaic sand deposits overlie the Utsira Formation and Eir formation (informal) with a hiatus. In the wells we have investigated, there is sand-sand contact at the boundary, consequently we regard the Upper Pliocene sand as a part of the large Utsira-Skade aquifer system. The Upper Pliocene sand has previously often been assigned to the Utsira Formation. The top of the sand is found at about 150 m below the sea floor in the Norwegian sector. Seismic data indicates that the latest active progradation of these sands took place towards the north-east in the Tampen area, where their distal parts interfinger with glacial sediments derived from Scandinavia.

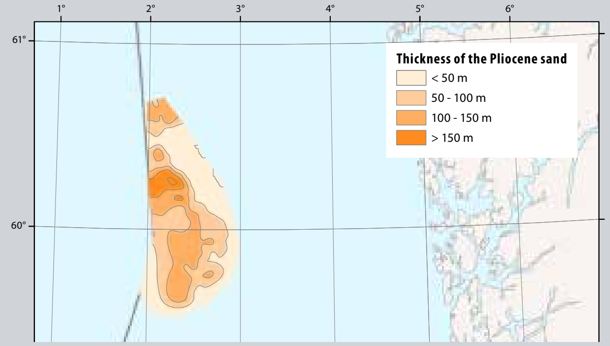


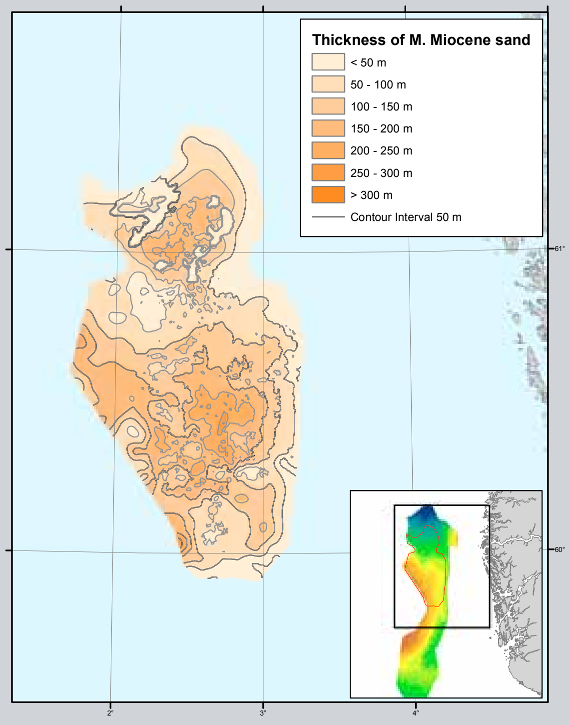


WELL LOG 24/12-1









The Hordaland Group - Claystones

Eocene to Lower Miocene, possibly Middle Miocene in the Central Graben

The Hordaland Gp has its type area in the North Sea Basin. The main lithology of the group is marine claystones with minor sandstones. Within the Hordaland Gp, four sandstone formations are defined: The Frigg, Grid, Skade and Vade Fms.

Maximum thickness of the group varies from 1100-1400 m in the central and southern part of the Viking Graben, thinning towards the margins. Thicknesses of wells in the type area (wells 2/2-1 and 24/12-1) are 1060 m and 1365 m. In the northern Viking Graben the group is only a few hundred meters thick. The group was deposited in an open marine environment. The base of the Hordaland Gp is the Balder Fm or sands of the Frigg Fm.

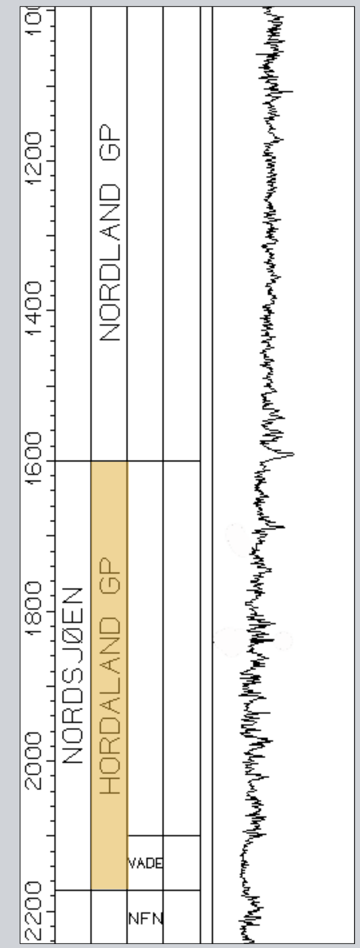
The Skade Fm is in communication with overlying Miocene and Pliocene sands and is described above.

The Frigg Fm (Lower Eocene) was deposited as submarine fans sourced from the East Shetland Platform to the west. The Formation is located in the south-western part of quadrant 30 and north-western part of quadrant 25. At about 59°30’N, the Frigg sands are connected to the sands in the UK sector. The thickness of the Frigg Fm is 279 m in type well (25/1-1) and it is located in a depocentre with a maximum thickness of approximately 300 m. The lower boundary is the Balder Fm and the upper boundary is claystones of the Hordaland Gp that could form a regional seal. The crest of the Frigg Field is approximately 1850 m and porosities and permeabilities are reported in the range of 27-32% and 1-4 Darcy, respectively.

The Grid Fm (Middle to Upper Eocene) consists of a series of sand-bodies probably sourced from the East Shetland Platform and located in the Viking Graben between 58°30’N and approximately 60°30’N. The type well is 15/3-3. The lower and upper boundaries are towards marine claystones of the Hordaland Gp. The thickness in the type well is 370 m. The formation thins eastward. There is a considerable difference in thickness north and south of 590N. To the north the thickness is less than 200 m and to the south nearly 400 m. This is due to the fact that sand deposition started earlier in the south. Due to soft sediment deformation, there may be poor connectivity between individual sand bodies, and some sands may be interpreted as injectites. The deposition of the formation took place in an open marine environment during regression.

The Vade Fm (Upper Oligocene) is defined in well 2/2-1 located on the Sørvestlandet High, east of the Central Graben. The lower and upper boundaries are claystones of the Hordaland Gp. In the type well the thickness is 72 m, but the formation has only been penetrated by a few wells. Regional considerations indicate a source area for the Vade Fm sandstones to the east or north-east. They were deposited in a shallow marine environment in 11/10-1 and prograded into deeper waters to the west as shown in well 2/2-2.

WELL LOG 2/2-1



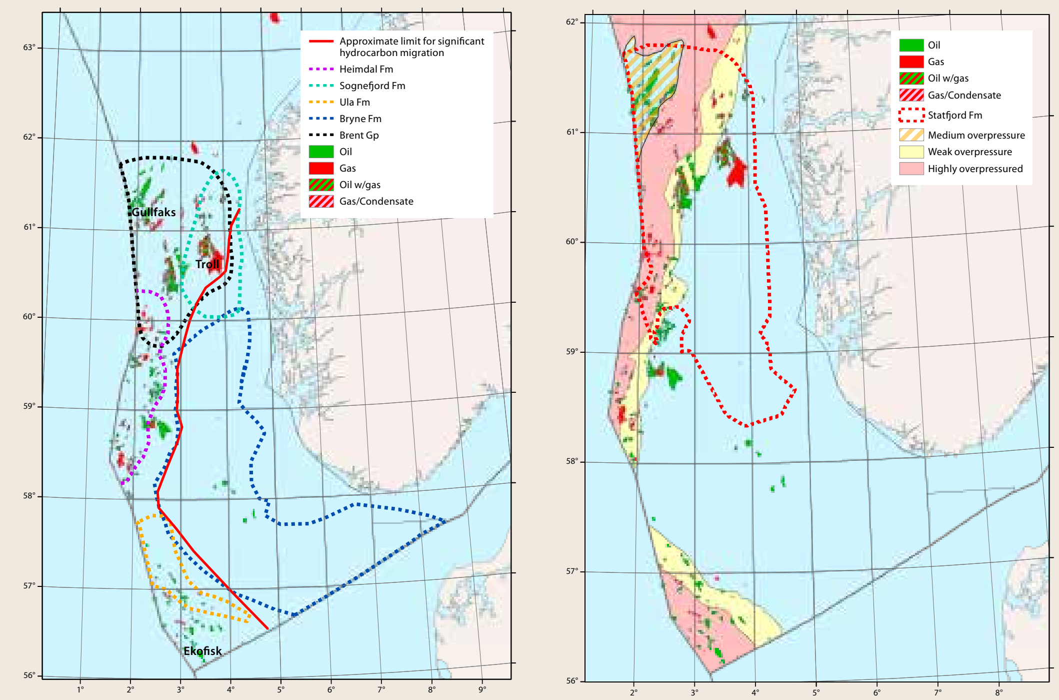
4.2.1 Saline aquifers

Introduction

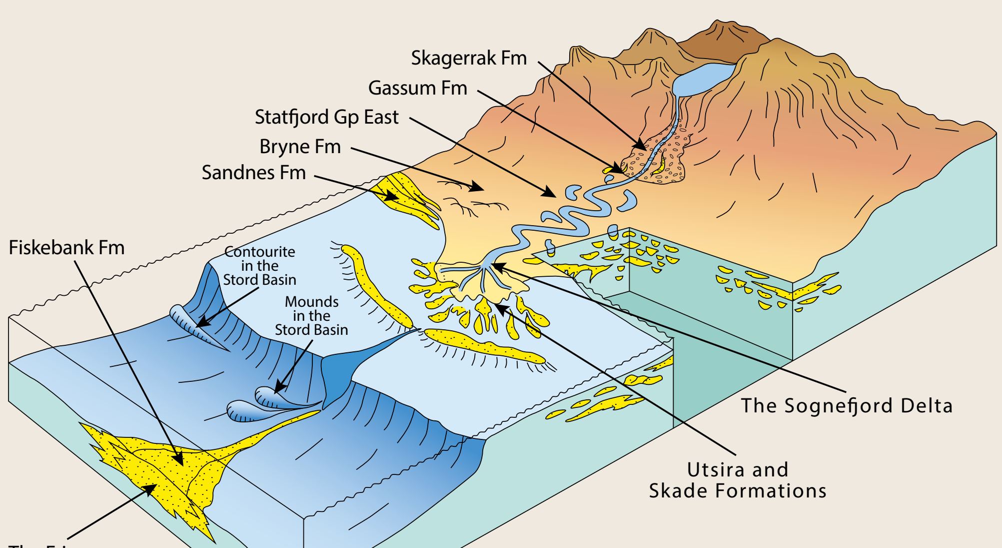
In the western provinces, west of the red line in the lower middle figure, Paleogene and older aquifers contain hydrocarbons. East of the line, discoveries have only been made in local basins where the Jurassic source rock has been buried to a sufficiently high temperature to generate hydrocarbons.

In the eastern area, all the large aquifers have been selected based on the established criteria (section 3.3) and storage capacity is estimated by the method described in section 3.4. In the petroleum provinces, it is considered that exploration and production activities will continue for many years to come. The most realistic sites of CO_2 storage will be some of the abandoned fields, in particular the gas fields. Consequently, an indication of the storage capacity of the fields has been given, but no aquifer volumes have been calculated. Some of the oil fields are considered to have a potential for use of CO_2 to enhance oil recovery (EOR, section 8). Some of the CO_2 used for EOR will remain trapped. The capacity for this type of CO_2 trapping has not been calculated.

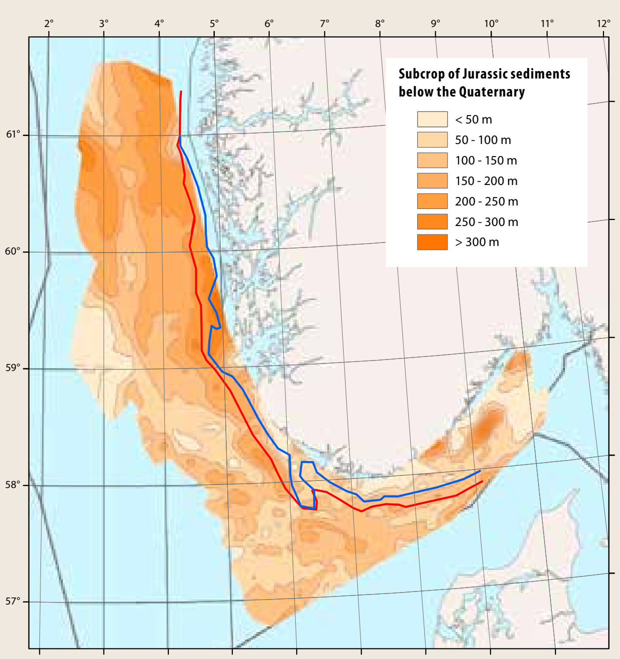
The Sognefjord Delta aquifer and the Statfjord Formation aquifer (figure) are developed both within the petroleum provinces in the west and as saline aquifers with small amounts or no petroleum in the east. In these cases, only the eastern parts have been evaluated for CO_2 storage.



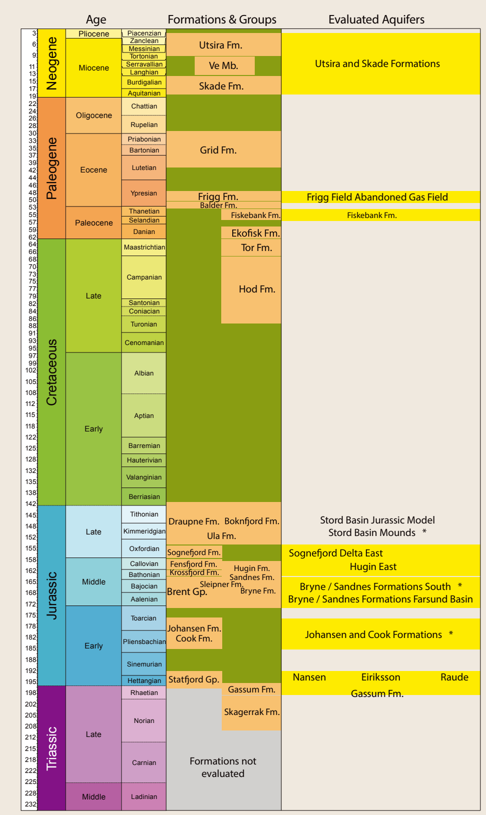
Distribution of major aquifers at the Jurassic levels relative to the petroleum provinces



Conceptual sketch showing location of aquifers relative to depositional systems



Thickness of Quaternary deposits and Jurassic subcrop



* Evaluated prospects

4.2.1 Saline aquifers

Stord basin - long distance CO_2 migration

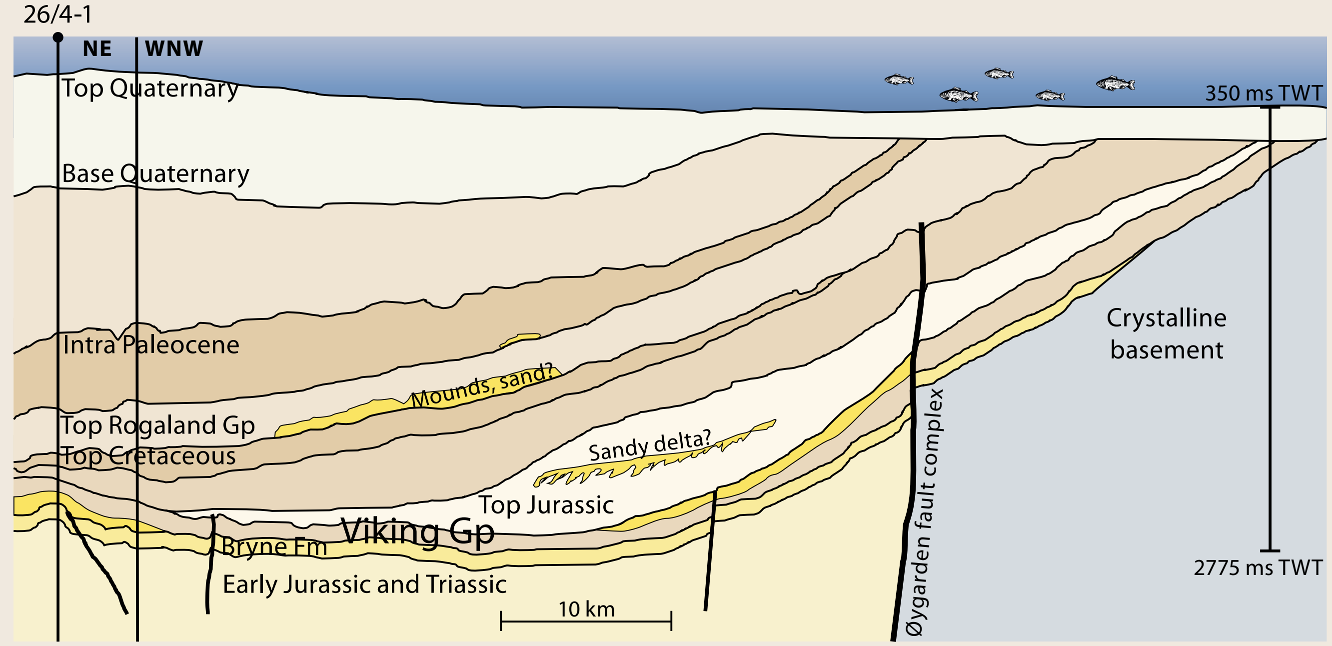
Modelling of CO_2 injection and migration in the Stord basin. The aquifers in the eastern part of the North Sea typically have a consistent dip of about one degree from the Norwegian coast down to the basinal areas. In the case that there are permeable beds along this dip slope, there is a risk that CO_2 injected in the downdip aquifer can migrate up to where the aquifer is truncated by Quaternary glacial sediments. At that depth, the CO_2 will be in gas phase. The glacial sediments mainly consist of clay and tills and their thickness ranges from about 50 m and up to more than 200 m (figure). Understanding the timing and extent of long distance CO_2 migration is of importance for the evaluation of the storage capacity of outcropping aquifers. Consequently, a modelling study was set up on a possible aquifer in the Stord Basin.

The Stord Basin is bordered by faults between the Utsira High in the west and the Øygarden fault complex in the east. The syn-rift basin acted as a depocentre for infilling sediments from all surrounding highs, the main source being the eastern hinterland. The basin is overlain by post-rift sediments ranging from late Jurassic to Quaternary age. Sand is mainly found in the Triassic and Jurassic. The main risks of leakage of injected CO_2 in the Stord basin area are sideways migration towards the east, and migration along fault planes. Absence of syn-rift sedimentary rocks on the upthrown side of the Øygarden fault complex may reduce the risk of sideways migration in this section.

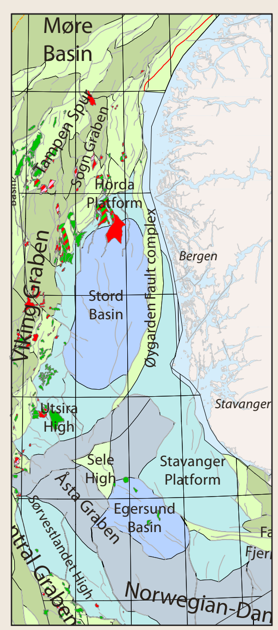
A simulation model of a possible Upper Jurassic sand deposit (referred to as Sandy delta in the cross section) was built based on a geological model derived from seismic interpretation. The model shown in the figure has been used to simulate CO_2 injection in the sand deposit, which will act as an aquifer.

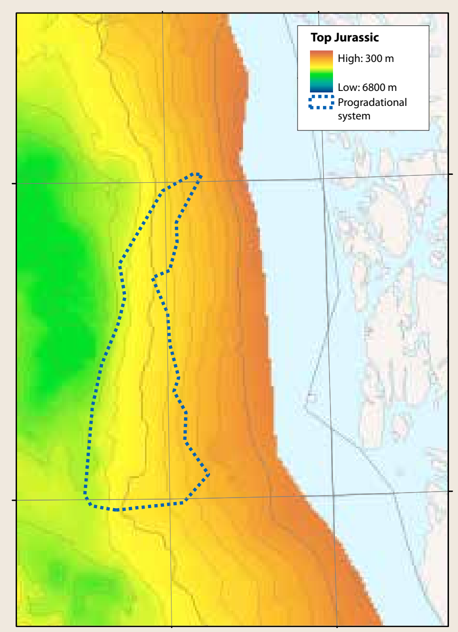
The modeled depositional system has not been drilled, and the interpretation is based on seismic 2D data. Although there is a reservoir risk in this particular model, the results can be applied to analogous aquifers with gentle dips.

Three injection wells are shown in the areas with highest permeability (green). A water producer is located on the east side of the grid, acting as a leaking point in the shallowest part. The permeability and porosity distribution around well 1 is shown in the profiles. The model was run with 50 years of injection with different rates. After shut-in of injection, migration continued until the CO_2 had migrated up to the east side of the model and begun to enter the Quaternary formations above. The simulations were run with one, three and five wells.



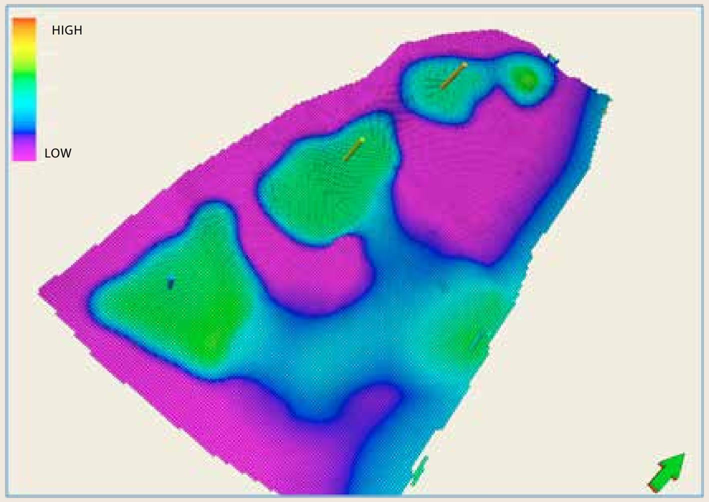
Seismic panel including well 26/4-1, Stord basin



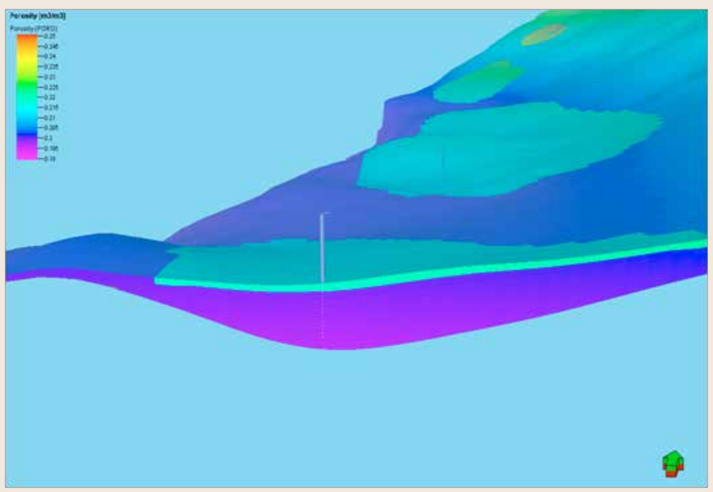


Polygon depicting modelled aquifer

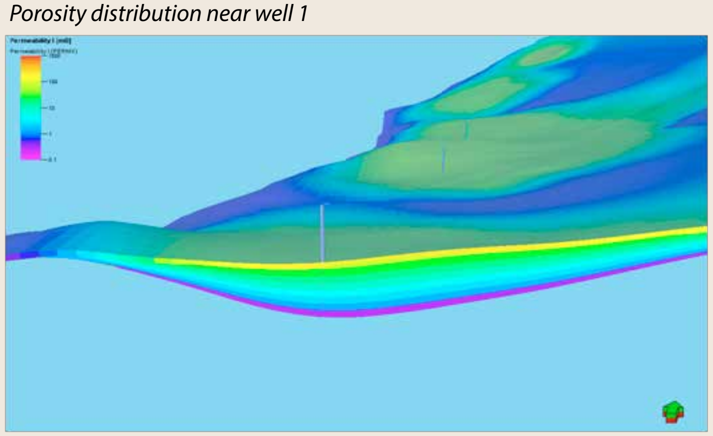
Stord basin - long distance CO_2 migration



Permeability in upper layer 1



Porosity distribution near well 1



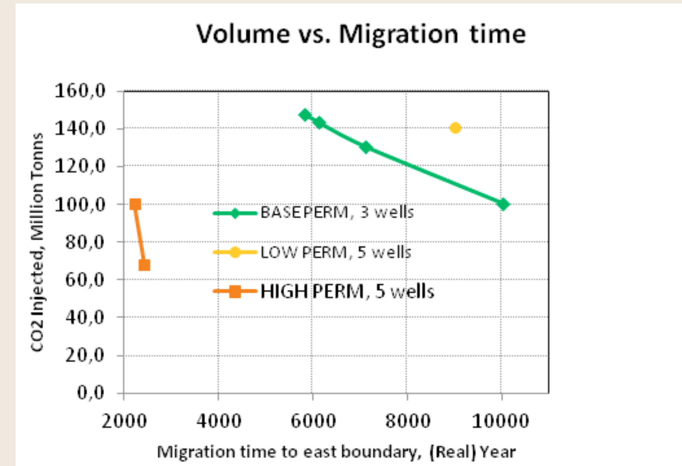
Porosity distribution near well 1

Three cases with different x-y permeabilities were run. Near well 1 the permeabilities vary from 0.14 mD in the bottom layer, to 199 mD in the top layer. The cases were run with the following model setups:

1. Base model
2. High perm model (permeability 20 times base case in top layer)
3. Low perm model (0.5 times base permeability in all layers)

The results for the different models are shown in the figure, with three and five wells.
The results show that in the base model with 3 mill Sm^3/d, the reservoir can store 100 Mt CO_2 before CO_2 reaches the eastern boundary of the reservoir in the year 10 000. If extrapolated to 10 000 years of storage, the maximum amount stored will be about 75 Mt. With a high permeability layer at the top (high case), and 3 mill Sm^3/d, the CO_2 will reach the boundary in year 2416 after about 400 years of migration.

When the CO_2 reaches the eastern boundary it is in gas phase and might migrate slowly upwards into the overlying Quaternary layers as discussed above.



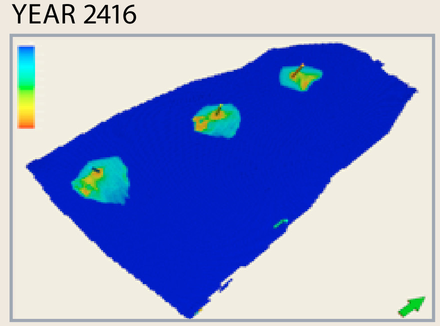
Volume of CO_2 injected vs. migration time

Conclusions

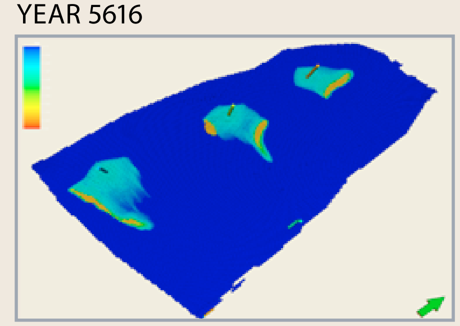
The results show that the CO_2 plume is distributed mostly in the high permeability (upper) layers of the reservoir.

With the base permeability model, about 100 Mt is the maximum storage capacity with migration for about 8000 years to boundary (year 10 000), if 3 mill Sm^3/d is injected in three wells. Higher rates will give a shorter migration time. With the low perm model and 9 mill Sm^3/d with five wells, the injected volume might be up to 140 Mt. A high permeability streak in the top layer will result in a short migration time, about 400 years. Low permeability and favourable communication reduces the risk of CO_2 escape. The results indicate that migration velocities are slow unless the permeability and communication are very high, implying that subcropping aquifers could be of interest for CO_2 storage.

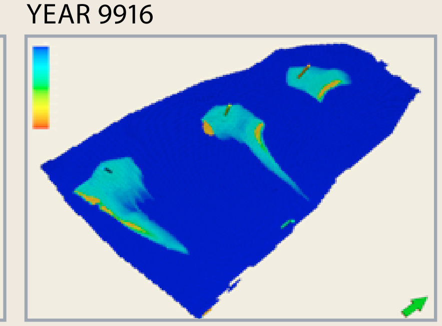
YEAR 2416



YEAR 5616



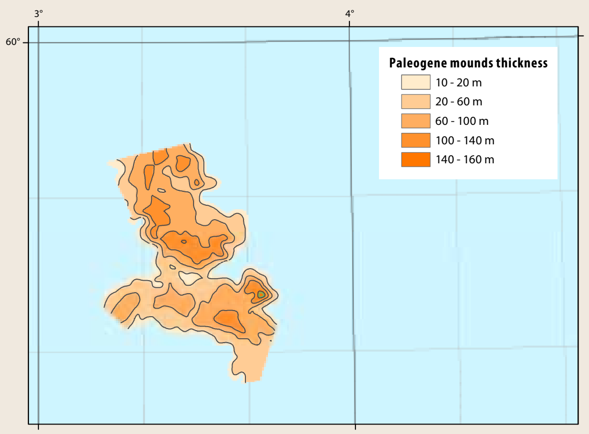
YEAR 9916

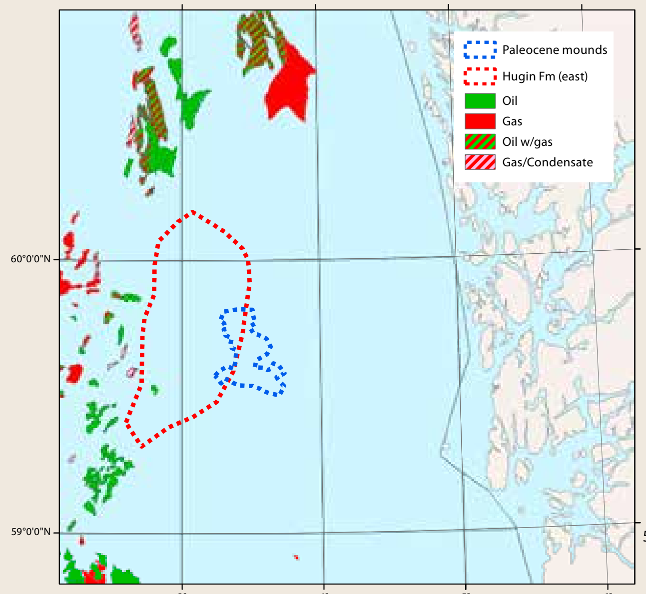


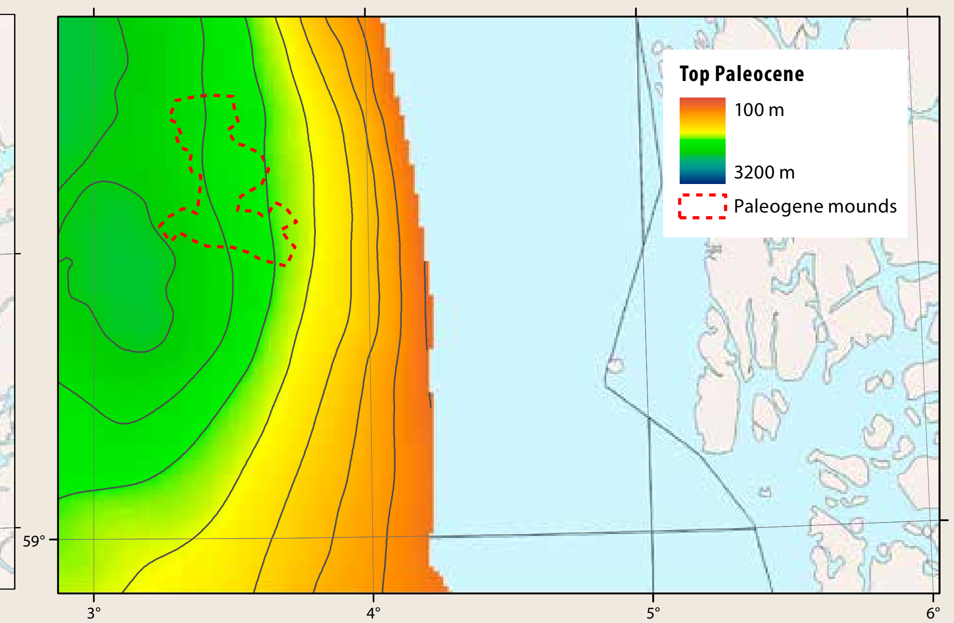
Volume of CO_2 injected vs. migration time

4.2.1 Saline aquifers

Paleogene Mounds, Stord Basin
The Hugin East Formation aquifer





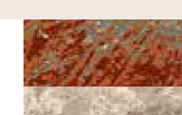


Paleogene mounds
This prospect is based on seismic 2D interpretation on a mounded reflector in the Paleocene/Eocene sequence in the central part of the Stord Basin. The reflection pattern has been interpreted as a possible deep marine fan system which could have a high content of reservoir sand. There are few wells in the area, and sand have not been proved by drilling in this particular interval. If sand is present, the mapped structure can be regarded as a structural/stratigraphical trap with good seals. The aquifer outside the mapped structure is considered to be limited. Calculation of storage capacity is based on 28 % porosity and a net gross ratio of 0.8 within a closed aquifer volume.

Hugin East Aquifer
One well has been drilled in this aquifer, which has been mapped on 2D seismic data. The reservoir rock is equivalent to the Hugin and Sandnes Formations, and is believed to have good quality. A simplified calculation of theoretical storage capacity was carried out, using a constant net gross value and a porosity trend similar to the Sandnes Formation.

Mounds, Stord basin		
Storage system	half open	
Rock volume		45 Gm^3
Pore volume		9.7 Gm^3
Average depth		1900 m
Average permeability		1000 mD
Storage efficiency		0.8 %
Storage capacity aquifer		
Storage capacity prospectivity		50 Mt
Reservoir quality		
	capacity	2
	injectivity	2
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		

Hugin fm east of the Utsira High		
Storage system	half open	
Rock volume		19 Gm^3
Pore volume		2.4 Gm^3
Average depth		1700 m
Average permeability		500 mD
Storage efficiency		5.5 %
Storage capacity aquifer		100 Mt
Storage capacity prospectivity		
Reservoir quality		
	capacity	1
	injectivity	3
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		



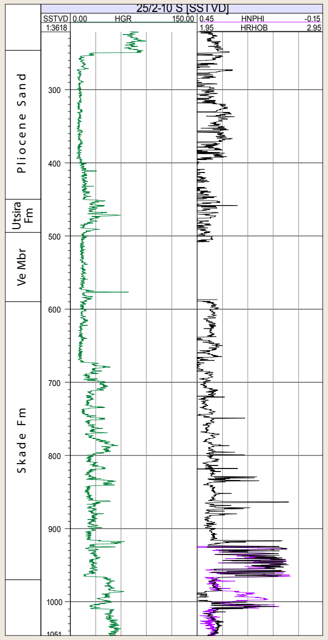
4.2.1 Saline aquifers

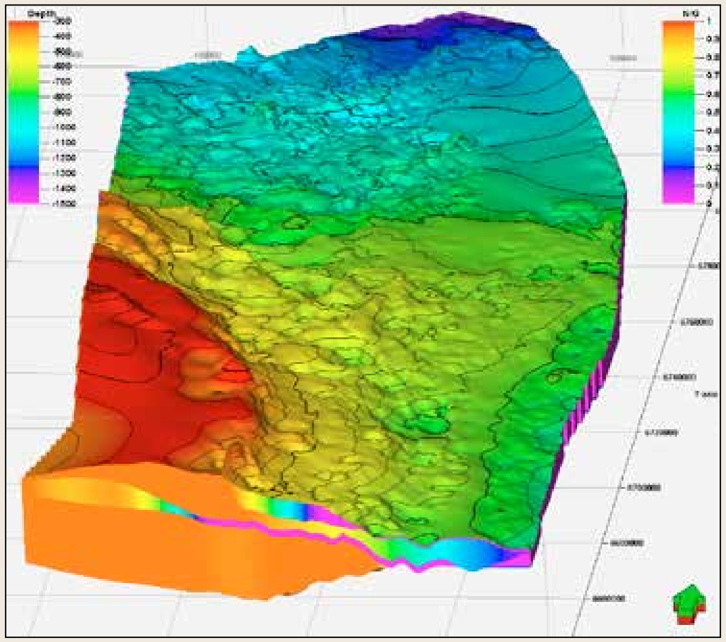
The Utsira and Skade aquifer

Approximately 1 Mt CO_2 from the Sleipner Field has been successfully injected annually in the Utsira Formation since 1996, proving that the formation is an excellent reservoir for CO_2 storage. Due to its size, the formation has been regarded as attractive for storage of large volumes. However, the formation is part of a much larger sandy deltaic complex located at both sides of the UK-Norway boundary. The upper parts of this system are buried to less than 200 m below the sea floor, and the communication between the different sandy formations has not yet been studied in detail. In this atlas we present the results of an NPD study based on 3D seismic interpretation and biostratigraphy. The Miocene and Pliocene aquifer is subdivided into four major units which are in communication towards the west. The largest pore volumes in the system are in the Utsira and Skade Formations, which appear to be separated by a Middle Miocene shale in the eastern/distale parts. There is a regional dip upward towards the west, and consequently there is a risk that injected CO_2 will migrate updip to levels which are too shallow to be accepted for storage. Three areas are assumed suitable for CO_2 injection:

1. The southern part of the Utsira Formation below approximately 750 m. This area has several structures which could accumulate CO_2 and prevent it from migrating upslope. Large volumes can also be trapped as residual and dissolved CO_2 in the aquifer.
2. Volume in the NE part of the Utsira Formation. This part of the Utsira Formation is in communication with a delta which was built out from the Sognefjord area in the east. The top of the eastern fan reaches the base of the Quaternary and it has not been evaluated for storage.
3. The outer part of the Skade Formation where it is sealed by Middle Miocene shale and could be trapped within structures formed by clay diapirism.

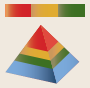
Pore volumes for this aquifer are presented together with storage capacities calculated for the three suggested sub- areas.

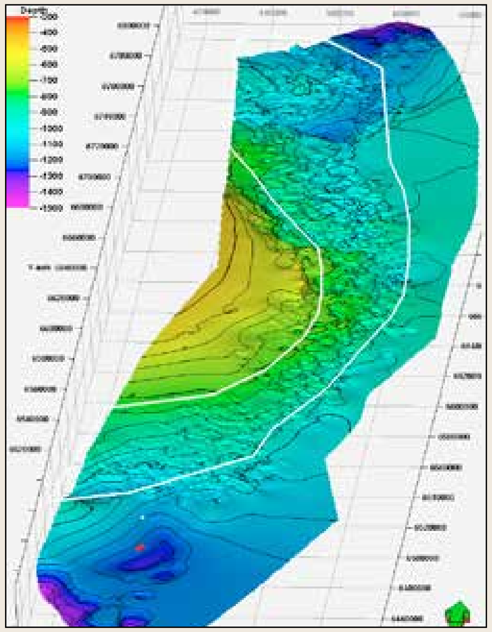




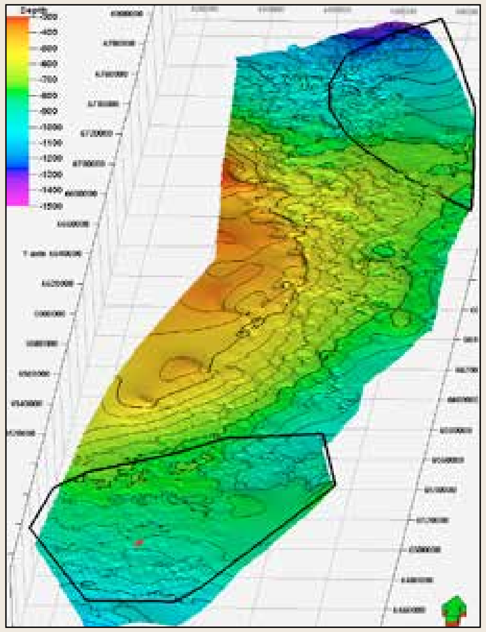
Cross section and top surface of the aquifer model. Cross section shows net-gross values.

Utsira and Skade Fms		
Storage system	half open to fully open	
Rock volume		2500 Gm^3
Pore volume		526 Gm^3
Average depth		900 m
Average permeability		>1000 mD
Storage efficiency		4 %
Storage capacity aquifer		16 Gt
Storage capacity prospectivity		0,5-1,5 Gt
Reservoir quality		
	capacity	3
	injectivity	3
Seal quality		
	seal	2
	fractured seal	3
	wells	2
Data quality		
Maturation		





Top of Skade Formation. The white polygon indicates area which may be favorable for CO_2 storage. Red dot shows Sleipner injection area. The grid squares are 20 km x 20 km.



Top of Utsira Formation. The black polygons indicate areas which may be favorable for CO_2 storage.

4.2.1 Saline aquifers

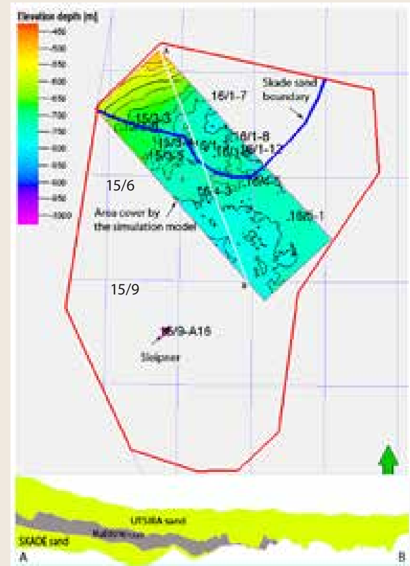
The Utsira and Skade aquifer

To estimate the capacity of CO_2 storage in a southern part of Utsira/Skade aquifer, a reservoir model was built to simulate the long-term behavior of CO_2 injection. The model covers 1600km^2 in the southern part of the Norwegian sector. The study illustrates potential migration and forecast possible migration of CO_2 from the Skade Formation into the Utsira Formation above.

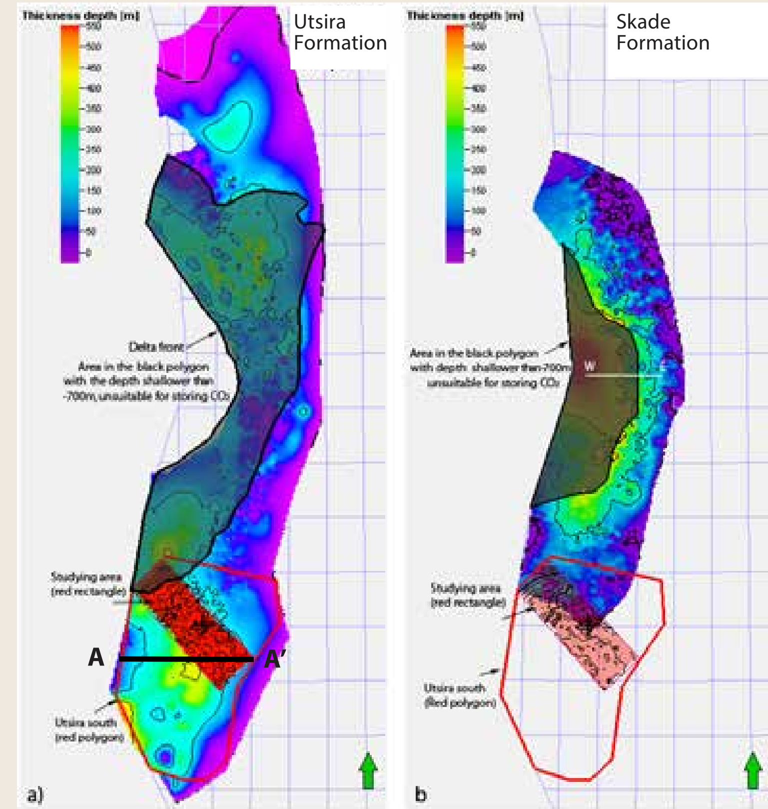
CO_2 injected in the Skade sand may penetrate through a intermediate clay layer into Utsira sand if the clay has permeability from 0.1 mD or higher. Approximately 170 Mt CO_2 can be injected in Utsira-Skade aquifer within the segment model, with four horizontal wells injecting over 50 years, with BHP change of 10 bars, and with no water production. After 8000 years of storage, the dissolved part is nearly 70%, residual trapping is less than 1%, and mobile CO_2 has decreased to 29% of the total amount of injected CO_2.

These results are based on a residual saturation of CO_2 of 0.02. If a residual saturation of CO_2 is 0.3, CO_2 trapped by residual mechanisms is 13% of total CO_2 injected after 8000 years. Mineral trapping by geochemical reactions was not considered in the simulation, but will add additional storage capacity.

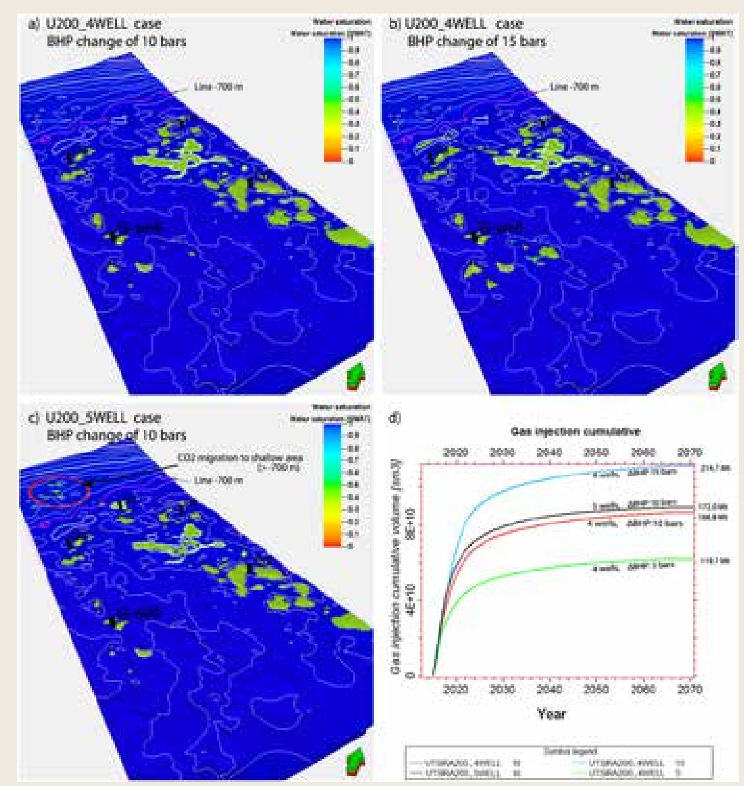
The NPD has calculated that 0.5-1.5 Gt of CO_2 can be stored in the southern area of the Utsira-Skade aquifer, based on in house simulation calculations.



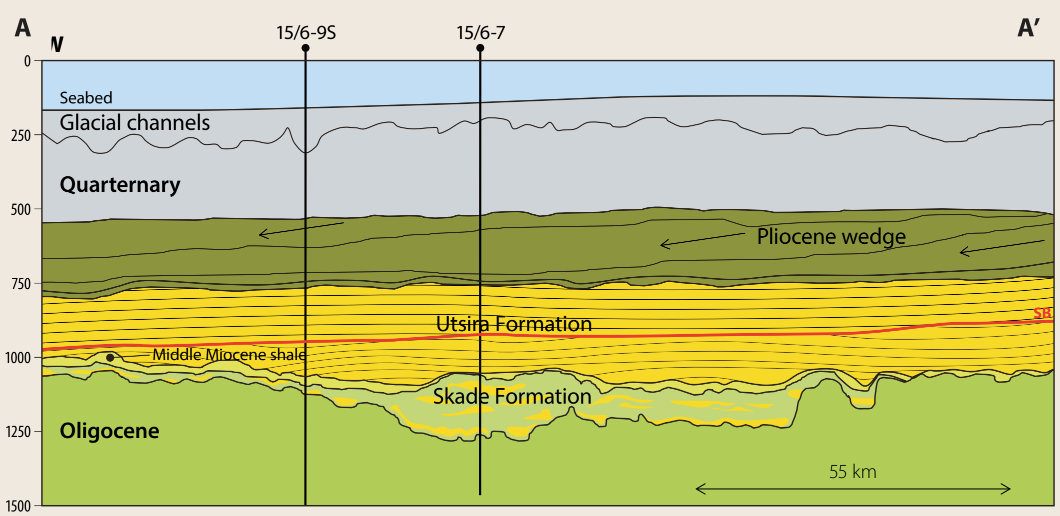
Red boundary defines the southern depocenter of the Utsira Formation. Skade Formation thins rapidly towards south and east, and is only observed as a few meters thick in well 15/6-7. The simulation model covers an area of 1600 m2 within the southern depocenter.



Thickness map (right) of Utsira and Skade Formations illustrating the extent of the formations and the area which is above 700 meters depth and thereby unsuitable for CO_2 storage.



8000 years after injection the CO_2 migrates and follows the topography and accumulates in surrounding structures. The graph illustrates that there is not much difference using 4 or 5 injection wells. The biggest difference occurs when there is an increase in the bottom hole pressure from 10 to 15 bars.



The Skade Fm, Lower Miocene, consists of marine sandstones (mainly turbidites) deposited over a large area of the Viking Graben (From 30/5-2 in the north, to 15/6-7 in the south). The maximum thickness exceeds 300 m and decreases rapidly towards the south and east, where the sands terminate towards large shale diapirs.

4.2.1 Saline aquifers

The Bryne and Sandnes Formations

The southern part of the Norwegian Sea has a well developed sandy sequence, which is made up of the Lower Jurassic, Sandnes and Bryne formations with occasional contact with the sands of the Triassic Gassum and Skagerrak formations. The fine grained, lowermost Jurassic Fjerritslev Formation, is partly developed as a seal between the Gassum and Bryne Formations.

The Sandnes formation is generally developed as a well sorted and widely distributed sand, above the thicker silt and sandstones of the Bryne formation. The vertical permeability of the Bryne formation is lowered by the coaly layers developed in most of the formation. The connectivity in the Bryne formation is hampered by the typical development of isolated channels and channel belts of the delta plain. The two formations typically thin on the crests of salt structures and thicken in the basins. The yellow polygon in the figure outlines the Farsund Basin. This basin is bounded by a basement high to the south, and has been treated as a separate segment within the aquifer.

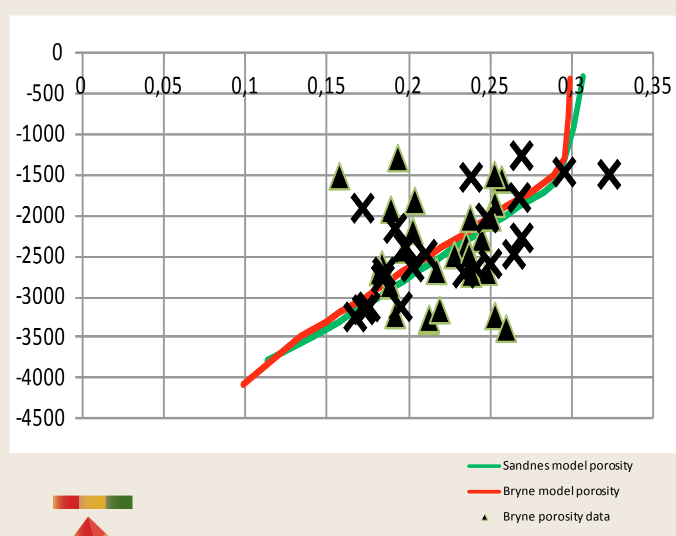
There is a limited amount of well data for constructing detailed petrophysical maps. In the present aquifer model, an average thickness is presented. For the porosity a general depth trend was applied, and for the net gross factor, a correlation to the formation thickness was attempted.

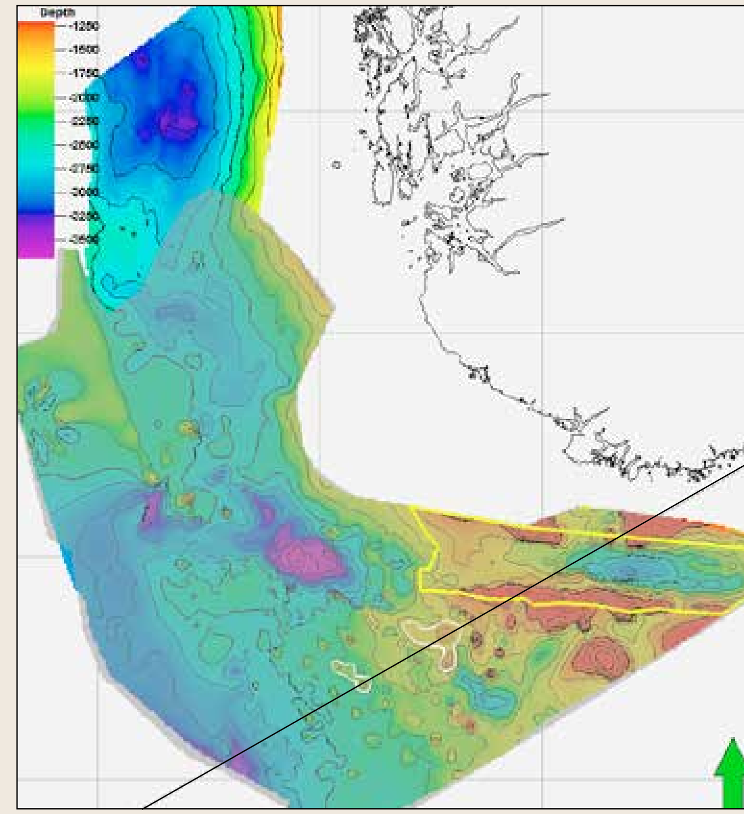
The aquifer is considered quite well suited for CO_2 storage due to the well developed reservoir rocks. The aquifer is capped by the generally thick and robust mud- and claystones of the Boknfjord Formation.

Seal integrity should be investigated further above salt structures and in major faults. To get an idea of the storage capacity of these structures is an estimation of two structural closures presented in the table. The smaller structure is thought to be representative for the aquifer. There also seems to be a possibility for larger structures in the saddle area between the Stord Basin and the Egersund Basin. Assuming that the aquifer could contain a few of the bigger structures and that there are many salt structures which could form prospects, a capacity range of 0.5 to 2 Gt for the prospects is assumed. The integrity and reservoir quality of each prospect would have to be investigated, hence they are assigned to level 2 in the pyramid.

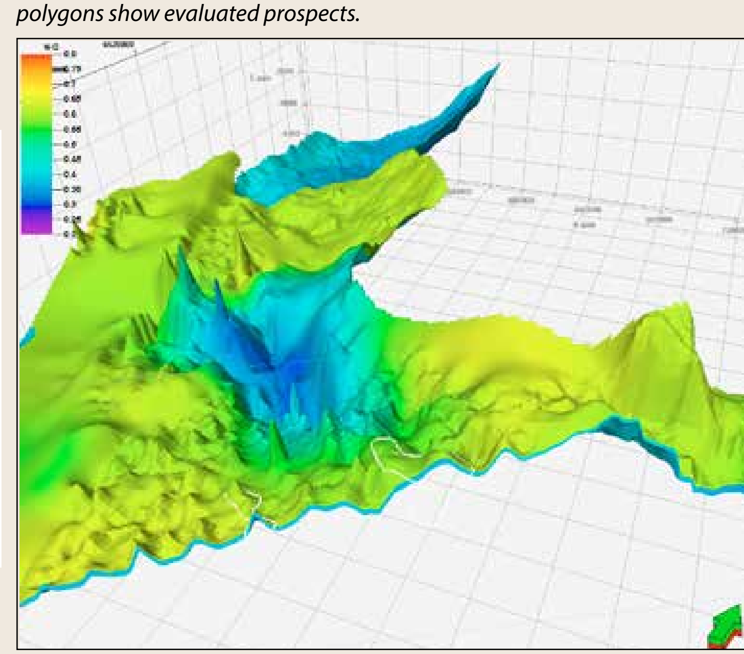
Farsund Basin		
Storage system	half open	
Rock volume		855 Gm^3
Pore volume		82 Gm^3
Average depth		
Average permeability		
Storage efficiency		4
Storage capacity aquifer		2 Gt

Bryne and Sandnes Fms		
Storage system	half open	
Rock volume		500 Gm^3
Pore volume		440 Gm^3
Average depth		1700 m
Average permeability		150 mD
Storage efficiency		4,5 %
Storage capacity aquifer		14 Gt
Storage capacity prospectivity		0,5-2 Gt
Reservoir quality		
	capacity	3
	injectivity	2
Seal quality		
	seal	3
	fractured seal	2
	wells	3
Data quality		
Maturation		





The Bryne and Sandnes aquifer. Yellow polygon shows Farsund Basin, white polygons show evaluated prospects.

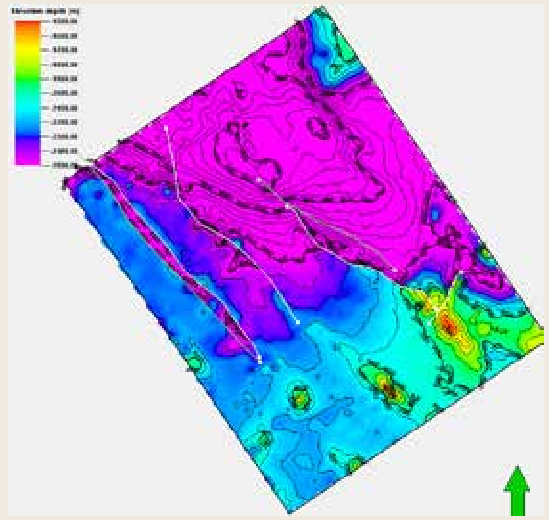

Top surface and cross section of the Bryne-Sandnes aquifer.

4.2.1 Saline aquifers

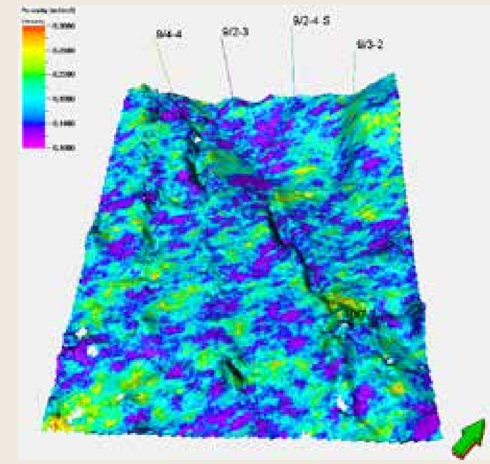
Egersund Basin case study

Geological model
The main target for CO_2 injection is the extensive middle Jurassic sands of the Sandnes and Bryne Formations in the Egersund Basin southwest of Stavanger. The Egersund Basin is a local deepening between the Norwegian-Danish Basin and the Stavanger Platform in the North Sea. The southern part of the basin is the focus for this study. The Egersund Basin has a small local oil kitchen to the NW, charging the Yme Field which is situated in the northern part of the basin. The development of lower and middle Jurassic sandstones is partly influenced by the tectonic structuring and salt movement. Later, the upper Jurassic – Lower Cretaceous tectonic development created a series of NW-SE faults. In the late Neogene the basin was lifted obliquely eastward and up towards the Norwegian mainland.
This is a promising area with good reservoir sand, well suited for containment of substantial volumes of CO_2. Migration of CO_2 into to salt structures penetrating the post Permian sequences and further into the Neogene, should however be avoided.

The Sandnes Formation contains marine sands with a high net/gross ratio, whereas the underlying Bryne Formation represents continental sand deposits with marine incursions. The lateral and vertical communication of the Bryne Formation is considered to be uncertain, and consequently it is not as suitable for large scale CO_2 injection. However, the Bryne Formation and some of the upper Triassic sands will contribute to the active aquifer volume. The reservoir sands are sealed by thick Jurassic and Cretaceous shales.

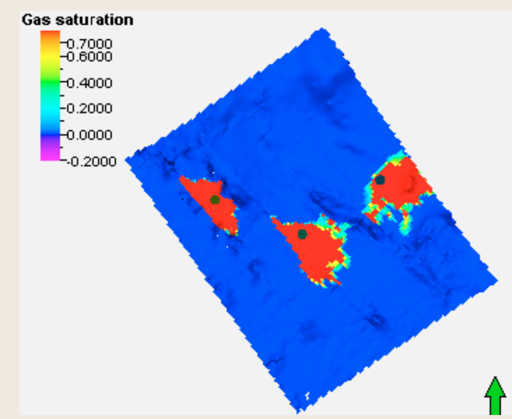


The simulated part of the Egersund Basin area.

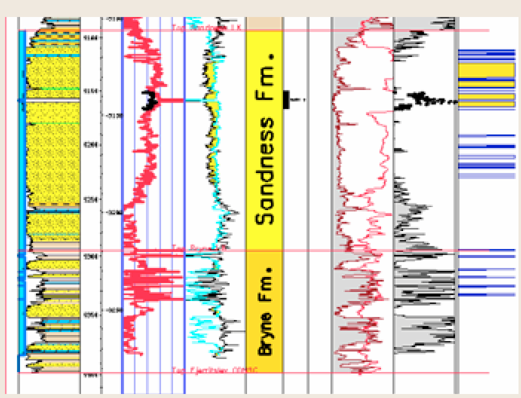


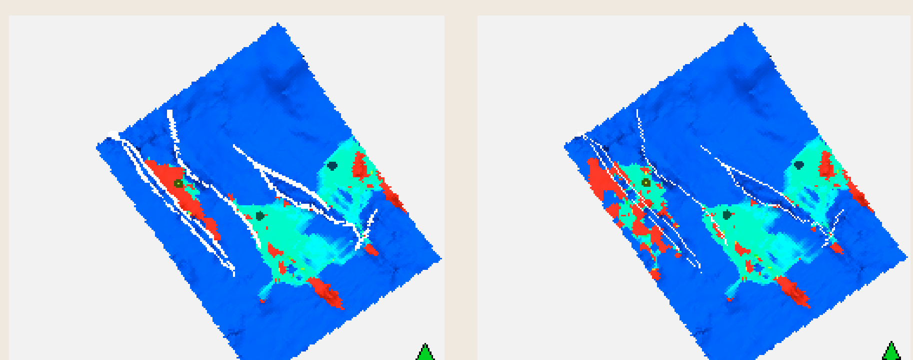
Porosity map of the uppermost layer of the Sandnes Formation used in the simulation

Results from the reservoir simulation of the Egersund Basin.
A segment model (48km x 62km) of the Egersund Basin was contructed to estimate the storage capacity and the migration paths. Different cases were run with 1-3 injection wells and injection rates from 2 to 10 MSm^3 CO_2/year in 50 years. Bottomhole pressure change is limited to 30 bar. Faults in the model were simulated with open and closed scenarios. Results showed that the volume of CO_2 injected is not very different between open and closed faults cases, but the distribution of the CO_2 plume is different (se figure).



CO_2 distribution after 50 years injection in three wells.





CO_2 distribution after 1000 year from injection start. With closed faults (left), and open faults (right). A part of the CO_2 migrates through the faults to the west.

Conclusion
Using the model and relative permeability curves from the Frigg field with a residual CO_2 saturation of 0.3, the storage capacity is:

- 180 GSm^3 or 0.36 Gigatons assuming a reservoir pressure buildup of 9 bar with 1 injector
- 546 GSm^3 or 1.1 Gigatons assuming a reservoir pressure buildup of 26 bar with 3 injectors

4.2.1 Saline aquifers

The Sognefjord Delta aquifer

The Sognefjord delta aquifer includes the sandstones belonging to the Viking Group. The Krossfjord, Fensfjord and Sognefjord Formations are partly separated by thin shale units (Heather Formation). Oil and gas production from the giant Troll Field has caused pressure reduction in all the three formations. The three formations are here treated as one aquifer. Influence of the Troll depletion on the aquifers in the older Jurassic formations is less pronounced. These sandy formations will be in communication through local juxtaposition along faults or by local sand-sand contact. In the area east of the Troll Field the sands are in direct contact with each other and constitute a good reservoir.

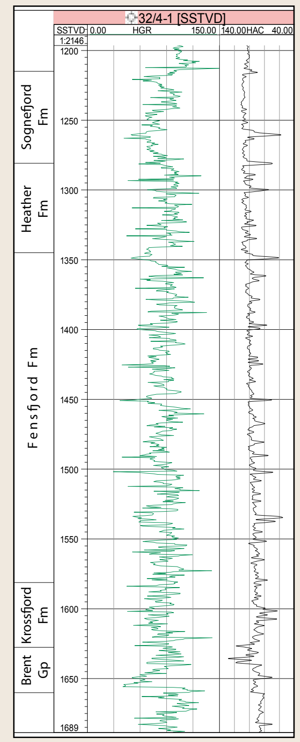
The storage capacity of the western part of the Sognefjord delta has not been included because it forms reservoir rock of the Troll field and other fields north of Troll. The aquifer is treated in the same way as in the main petroleum provinces.

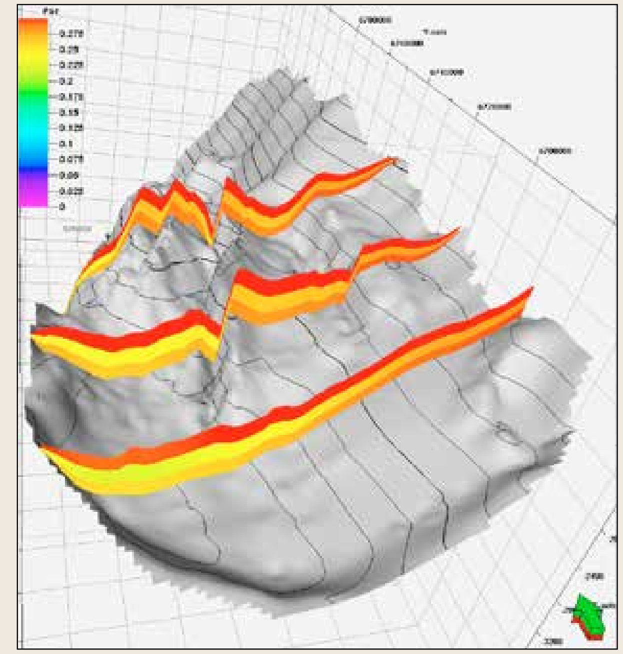
The eastern part of the Sognefjord Delta aquifer (within the black polygon in the figure) is structured by faults in the Øygarden Fault Complex. Two water-filled structural traps have been drilled in this area. This part of the aquifer is considered to be outside the area of large scale hydrocarbon migration, and closed structures may be attractive for CO_2 storage.

The porosity used for volume calculation is based on depth trends derived from wells in the area.

Several gas accumulations in the western part of the aquifer indicate a good quality seal. The sealing capacity of the fault zones in the Øygarden Fault Complex has to be investigated further. The aquifer subcrops below the Quaternary in the east, and there might be a risk of lateral migration of injected CO_2 towards the subcrop area.

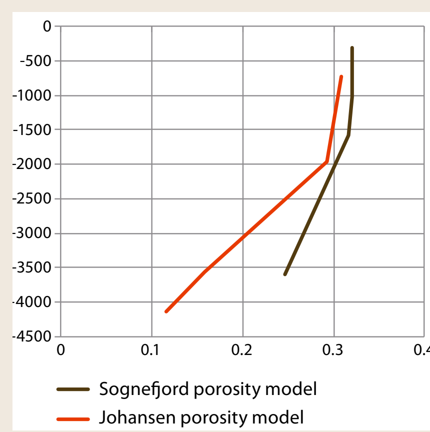
WELL 32/4-1

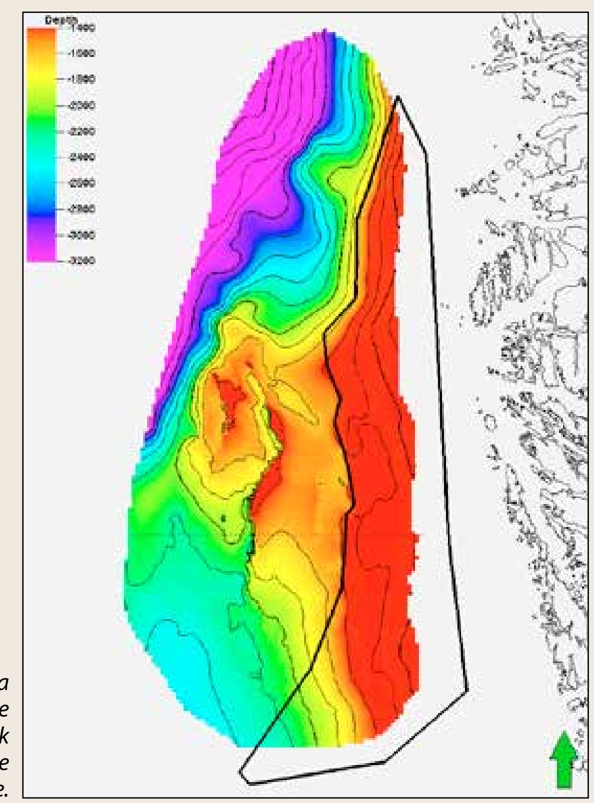




Cross sections showing the Krossfjord, Fensfjord and Sognefjord formations with modelled porosity values above the Top Brent surface within the Sognefjord Delta.

Sognefjord Delta		**Total aquifer Summary**	**East aquifer Summary**
Storage system	half open		
Rock volume		2670 Gm^3	554 Gm^3
Pore volume		480 Gm^3	110 Gm^3
Average depth		1750 m	1750 m
Average permeability		300 mD	300 mD
Storage efficiency		5,5 %	5,5 %
Storage capacity aquifer		18 Gt	4 Gt
Storage capacity prospectivity			
Reservoir quality			
	capacity	3	3
	injectivity	3	3
Seal quality			
	seal	3	3
	fractured seal	2	2
	wells	2	2
Data quality			
Maturation			





Top of the Sognefjord delta aquifer. The eastern past of the aquifer, outlined by the black polygon, is outside the petroleum province.

4.2.1 Saline aquifers

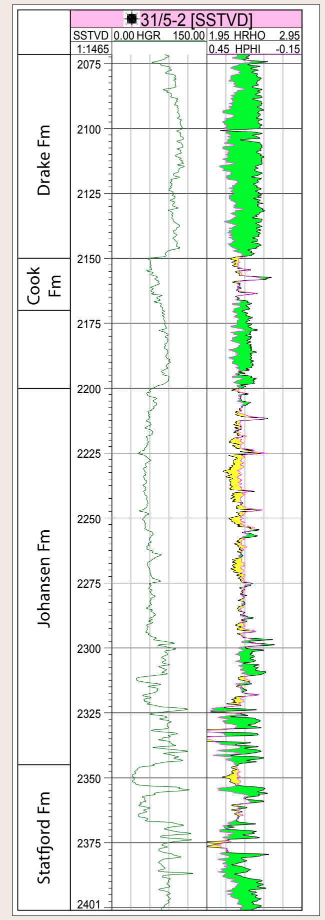
The Johansen and Cook Formation aquifer

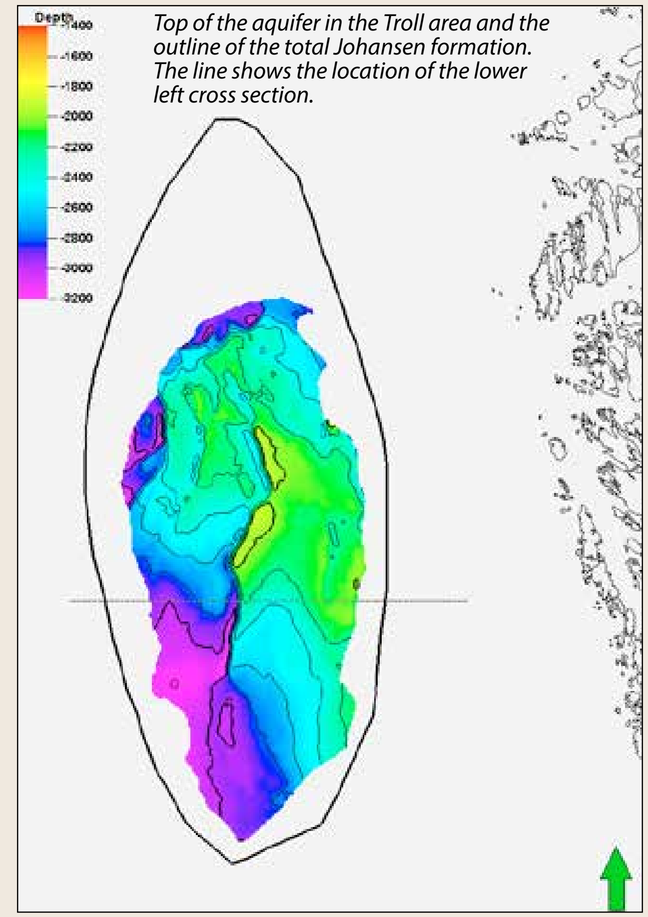
The Johansen and Cook Formations are mainly separated by shales and siltstones, but due to fault juxtaposition, they will be treated as one aquifer. The Johansen Formation sandstones have good reservoir properties in several wells in the Troll Field, and seismic data imply that the sand distribution is similar to the overlying Sognefjord Delta. The Cook Formation and the underlying Statfjord Formation extend to the Tampen Spur. The upper part of the Dunlin Group in the Troll area consists of the thick Drake Formation shale which is the main seal (figure).

The Johansen Formation south of the Troll Field was suggested by the NPD in 2007 as a potential storage site for CO_2 from Mongstad, and several studies have been carried out in order to qualify the aquifer for CO_2 storage. The NPD and Gassnova have acquired 3D seismic data in the most promising area. The studies indicate that the formation has sufficient capacity to store the volumes from Mongstad, but a well is important to clarify the reservoir and seal properties in the area south of Troll. Migration of CO^2 to the surface is unlikely due to the large capacity of the Sognefjord Delta aquifer.

The capacity of the Johansen and Cook aquifer depends on the communication within the aquifer, and if it is in communication with the Statfjord and/or the Sognefjord Delta aquifers across major faults.

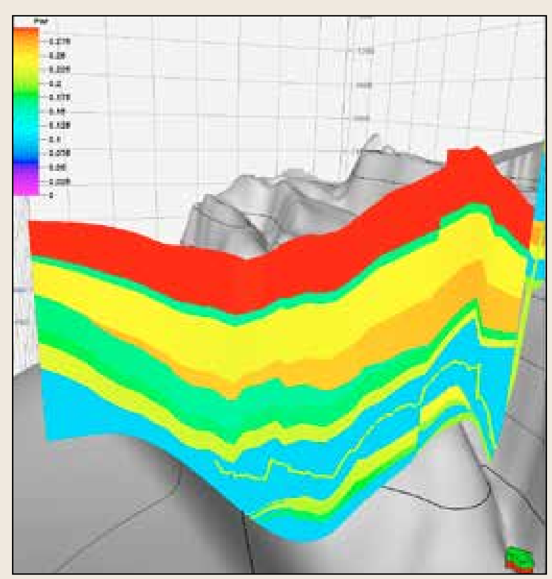
The pore volume and the storage capacity in prospects given in the table are based on calculations by Gassnova. These calculations do not include the northernmost part of the aquifer in the area north of Troll, see figure.



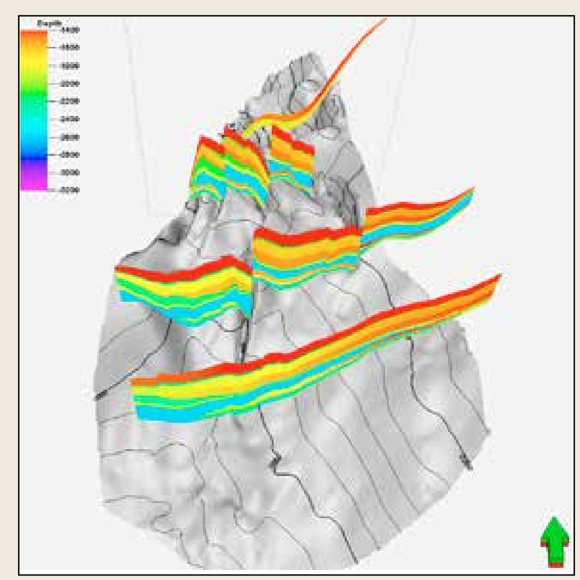


Top of the aquifer in the Troll area and the outline of the total Johansen formation. The line shows the location of the lower left cross section.

Cook Johansen aquifer		
Storage system	half open	
Rock volume		590 Gm^3
Pore volume		90 Gm^3
Average depth		1700 m
Average permeability		400 mD
Storage efficiency		3 %
Storage capacity aquifer		2 Gt
Storage capacity prospectivity		150 Mt
Reservoir quality		
	capacity	3
	injectivity	2
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		



Cross section of the porosity model of the Sognefjord delta. The Johansen and Cook Formations are the two deepest porous layers.



Several cross sections showing juxtaposition of porous formations across faults. The basal surface is the top of the Statfjord Formation.

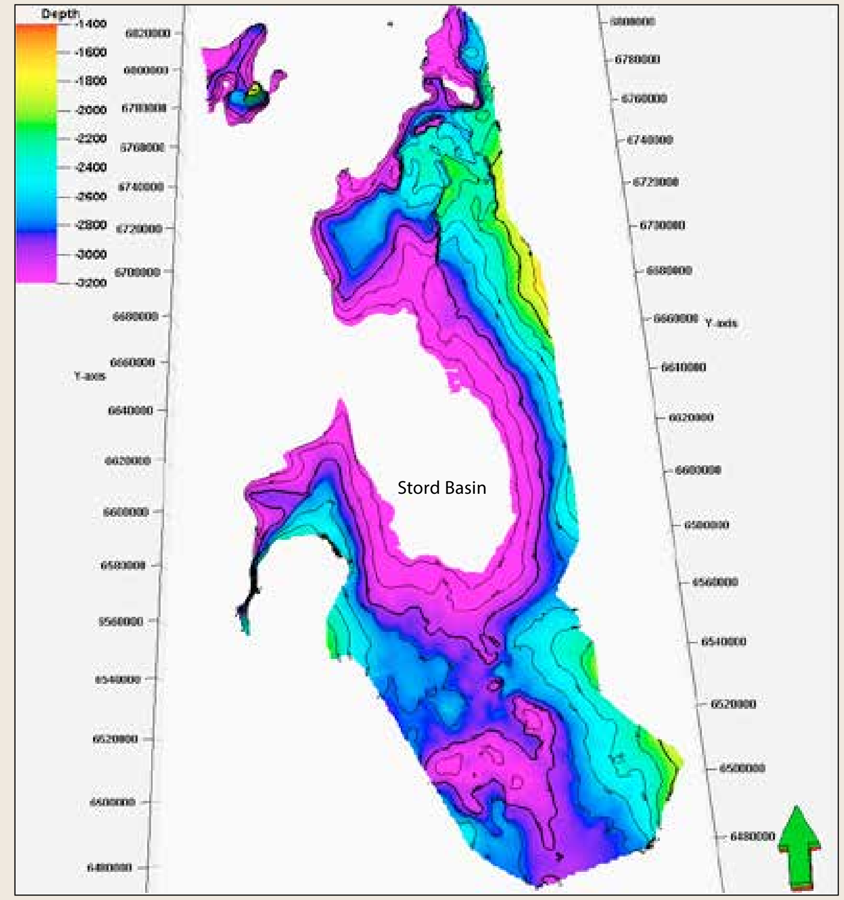
4.2.1 Saline aquifers

The Statfjord Formation aquifer

The Statfjord Formation contains hydrocarbons in the Viking Graben, Tampen High and north of the Stord Basin. South of the Horda Platform, it is assumed to be mainly water bearing. In the Stord Basin and its surroundings, it is separated from the overlying Jurassic aquifers by the Dunlin Group which is expected to form the seal. Towards the south and towards the Norwegian coast, the Lower Jurassic and large parts of the Middle Jurassic pinch out, and there may be communication between the Statfjord Formation aquifer and the shallower aquifers.

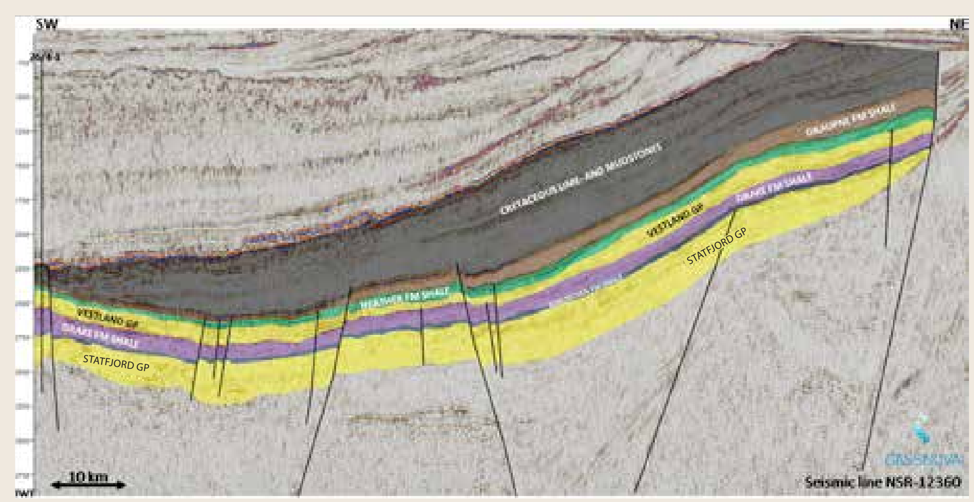
Few wells have been drilled in the Stord Basin area, and neither the formation properties nor its distribution and thickness are well known.

A heterogeneous formation with locally good quality reservoirs, but with limited lateral and vertical continuity can be expected. For the purpose of calculation of theoretical storage capacity, an average net gross of 50 % has been applied to the whole area and a porosity-depth trend similar to the Bryne Formation was applied. This is based on the general geological understanding of the area. In the Stord Basin (fig), parts of the formation are located below 3500 m, and has been excluded from the volume calculation.



The top of the Statfjord Formation above 3500 m. The Tampen area to the NW was not included in the volume calculations.

Statfjord Gp East		
Storage system	half open	
Rock volume		1130 Gm^3
Pore volume		120 Gm^3
Average depth		2400 m
Average permeability		200 mD
Storage efficiency		4,5 %
Storage capacity aquifer		4 Gt
Storage capacity prospectivity		
Reservoir quality		
	capacity	3
	injectivity	2
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		



SW-NE cross section in the northern part of the Stord Basin

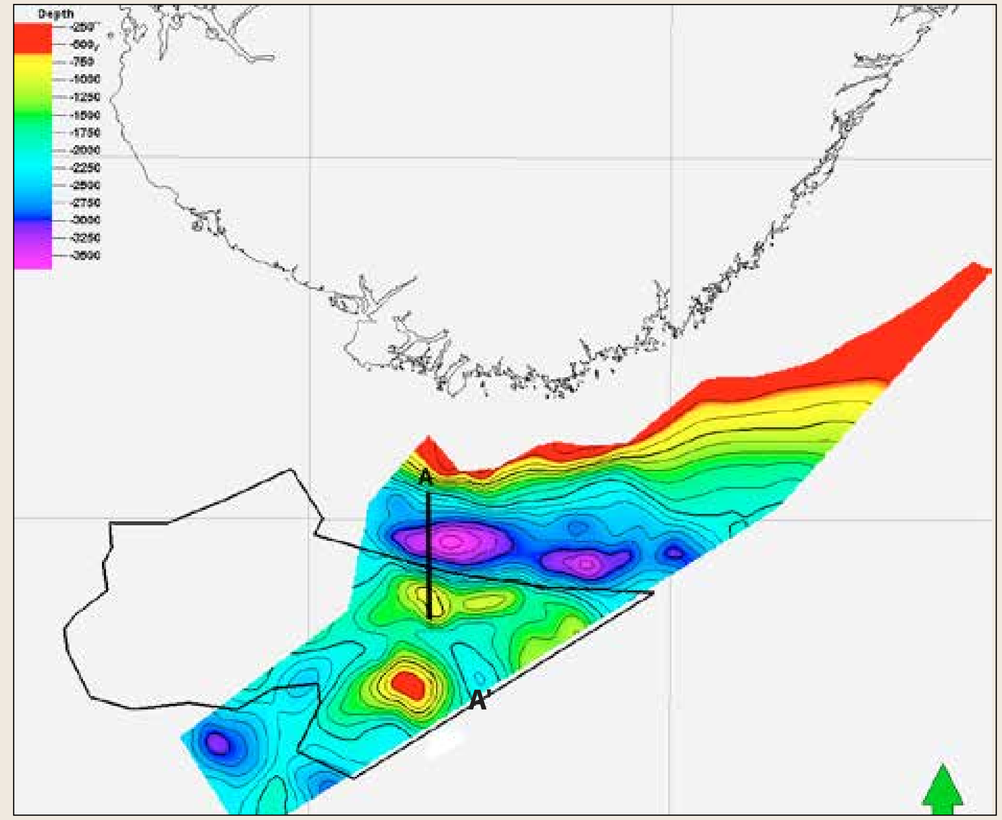
4.2.1 Saline aquifers

The Gassum Formation aquifer and the Skagerrak Formation

The aquifer was developed as river dominated system in the latest Triassic time, mainly as a well drained braided river system . The sandstones are believed to be of good quality. The type wells for these sandstones are in the Danish sector, and the Norwegian part is not explored in the same detail. Outside the mapped area indicated in the figure, the latest Triassic fluvial systems are more clay rich and are developed as discontinuous river sands. In the area indicated, the formation is sealed by the Fjerritslev Formation.

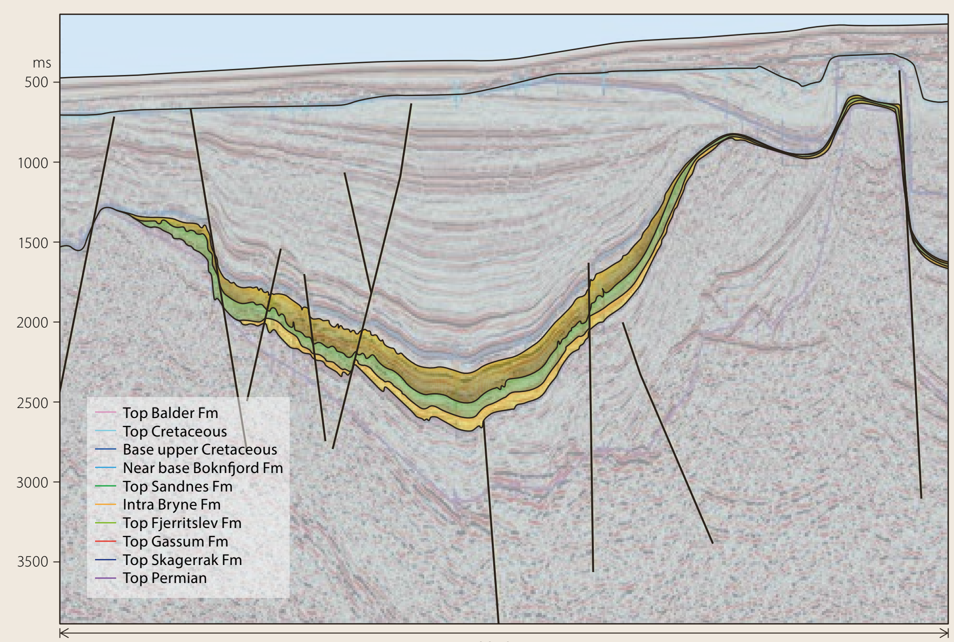
In the Skagerrak area, the Gassum Formation outcrops to the sea floor, and is covered by a Quaternary section which is typically less than 100 m thick. The sealing risks include faults, fracturing above salt structures and long distance migration towards the sea floor. The red areas in the map shows where the burial depth is less than 600 m. Migration of CO_2 into these areas should be avoided. The Gassum Formation can be a candidate for CO_2 injection in the Skagerrak area, but more data is required to investigate its potential.

The underlying Skagerrak formation is developed as a braidplain in an arid desert environment and as alluvium bordering the emergent land area east of the Danish-Norwegian Basin. Scarce well data indicate that the thick sandy sequences of the formation have low permeability, but locally they could interact with the overlying Gassum aquifer. The Skagerrak Formation in the Norwegian sector is poorly known, and with more data it is possible that a storage potential could be defined. In the figure, the outlined area indicates where the Skagerrak Formation is buried to less than 2000 m.



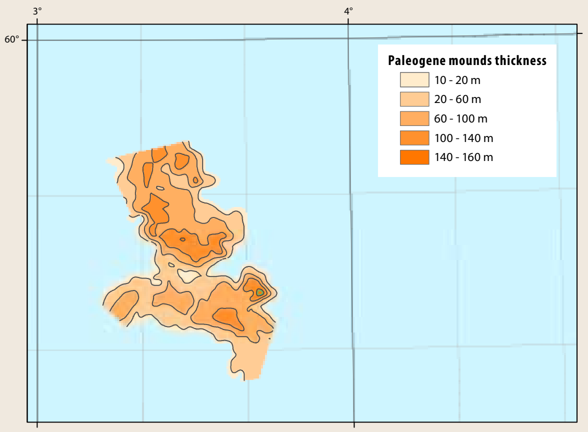
Top of the Gassum Formation

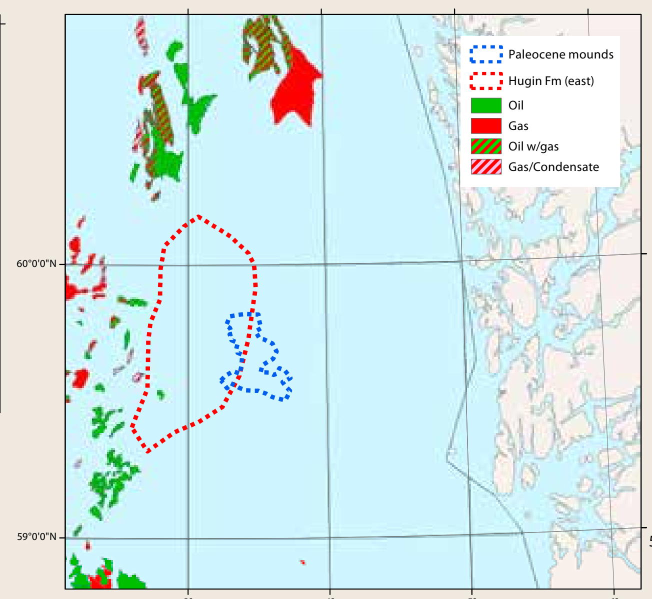
Gassum Fm		
Storage system	half open	
Rock volume		6500 Gm^3
Pore volume		756 Gm^3
Average depth		2200 m
Average permeability		450 mD
Storage efficiency		5,5 %
Storage capacity aquifer		3 Gt
Storage capacity prospectivity		
Reservoir quality		
	capacity	2
	injectivity	3
Seal quality		
	seal	3
	fractured seal	2
	wells	3
Data quality		
Maturation		

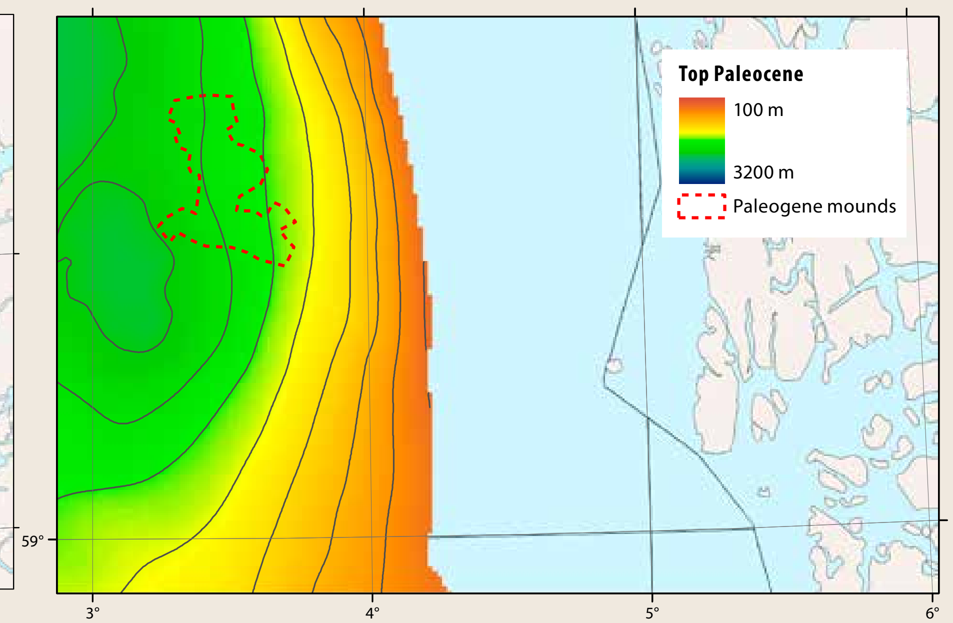


Seismic section across the Farsund Basin. The Gassum aquifer is located between the red and the dark blue horizon at the base of the Jurassic section.

Paleogene Mounds, Stord Basin
The Hugin East Formation aquifer







Paleogene mounds

This prospect is based on seismic 2D interpretation on a mounded reflector in the Paleocene/Eocene sequence in the central part of the Stord Basin. The reflection pattern has been interpreted as a possible deep marine fan system which could have a high content of reservoir sand. There are few wells in the area, and sand have not been proved by drilling in this particular interval. If sand is present, the mapped structure can be regarded as a structural/stratigraphical trap with good seals. The aquifer outside the mapped structure is considered to be limited. Calculation of storage capacity is based on 28 % porosity and a net gross ratio of 0.8 within a closed aquifer volume.

Mounds, Stord basin		
Storage system	half open	
Rock volume		45 Gm^3
Pore volume		10 Gm^3
Average depth		1900 m
Average permeability		1000 mD
Storage efficiency		0.8 %
Storage capacity aquifer		
Storage capacity prospectivity		50 Mt
Reservoir quality		
	capacity	2
	injectivity	2
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		

Hugin East Aquifer

One well has been drilled in this aquifer, which has been mapped on 2D seismic data. The reservoir rock is equivalent to the Hugin and Sandnes Formations, and is believed to have good quality. A simplified calculation of theoretical storage capacity was carried out, using a constant net gross value and a porosity trend similar to the Sandnes Formation.

Hugin fm east of the Utsira High		
Storage system	half open	
Rock volume		19 Gm^3
Pore volume		2.5 Gm^3
Average depth		1700 m
Average permeability		500 mD
Storage efficiency		5,5 %
Storage capacity aquifer		100 Mt
Storage capacity prospectivity		
Reservoir quality		
	capacity	1
	injectivity	3
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		

4.2.1 Saline aquifers

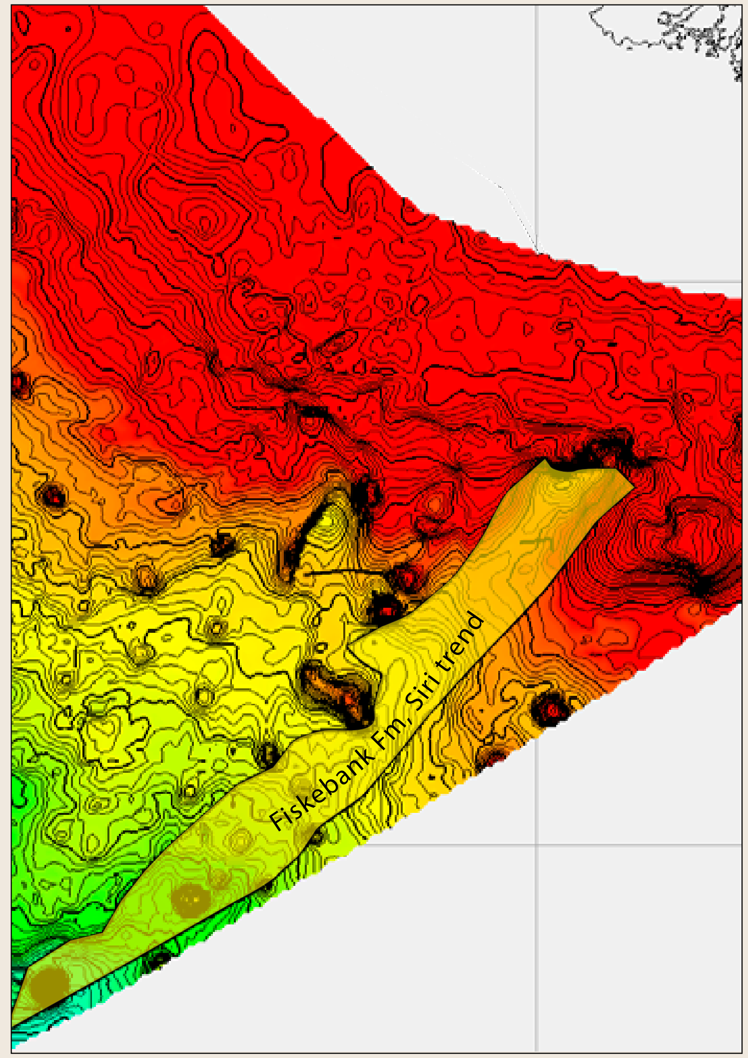
The Fiskebank Formation aquifer (The Siri trend)

In the Norwegian-Danish Basin, deep water sandstones of upper Palaeocene age, hold some smaller hydrocarbon fields and discoveries on the Danish sector close to the border with Norway. The sands on the Norwegian side have been drilled by the dry well 3/6-1 and are highly porous and permeable.

The suggested Fiskebank Formation aquifer is located in a depression in the top chalk surface as shown in the figure. More wells are needed to confirm the existence of high quality sands.

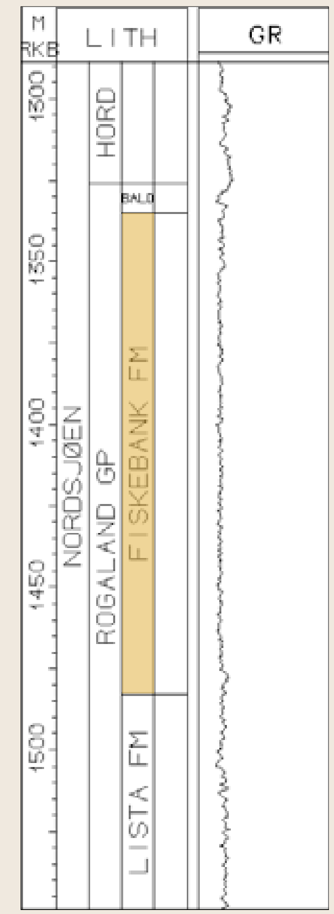
There is some hydrocarbon exploration activity in this area, which is not considered to be fully explored.
The sealing capacity of the Paleocene caprocks is generally thought to be good. Fracturing related to salt structures may occur.

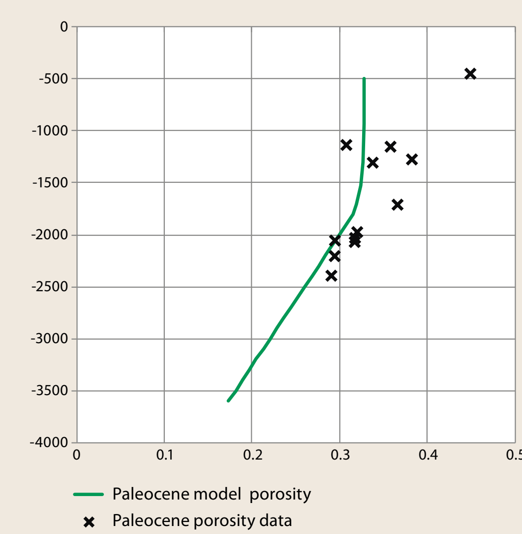
Fiskebank Fm, (Siri trend)		
Storage system	half open	
Rock volume		100 Gm^3
Pore volume		25 Gm^3
Average depth		
Average permeability		1000 mD
Storage efficiency		5.5 %
Storage capacity aquifer		1 Gt
Storage capacity prospectivity		
Reservoir quality		
	capacity	3
	injectivity	3
Seal quality		
	seal	3
	fractured seal	3
	wells	3
Data quality		
Maturation		



Top of the chalk surface. The polygon shows the location of the Fiskebank Formation aquifer.

WELL LOG 9/11-1





4.2.2 Abandoned hydrocarbon fields

Storage in abandoned fields

The estimate of CO_2 storage potential in the petroleum provinces is based on abandoned fields. This is in accordance with the Governmental policy that any negative consequences of CO_2 storage projects for existing and future petroleum activity should be minimized.

At the end of 2013 there are 12 abandoned fields on the Norwegian shelf. Of these three oil fields, four gas-condensate fields and five gas fields. Of the 12 fields, CO_2 storage volumes have been calculated for nine. The chosen fields have been pressure depleted, and the calculations are based on material balance, taking into account the produced volumes of oil, condensate and gas. Some of the fields are chalk fields in the Ekofisk area with low permeability reservoirs. To get decent injection rates, the wells need to be long with advanced completions. The fields have an EOR potential because they contain a rest of hydrocarbons that might be mobilized and produced during the injection. The CO_2 storage capacity for today's producing fields are estimated based on the close of the production year, and summarized for the years 2030 and 2050.

The Frigg field is studied in more detail and simulated due to its large storage potential. The fields and the main aquifers in the petroleum provinces in the North Sea are shown in the maps.

Many of the big fields in the Lower –Middle Jurassic Statfjord, Brent and Sleipner aquifers are located in areas with weak to moderate overpressure. In parts of the aquifers, the pressure has been depleted due to production. The highly overpressured parts of the aquifers (red color in the pressure maps) are not suitable for CO_2 injection.

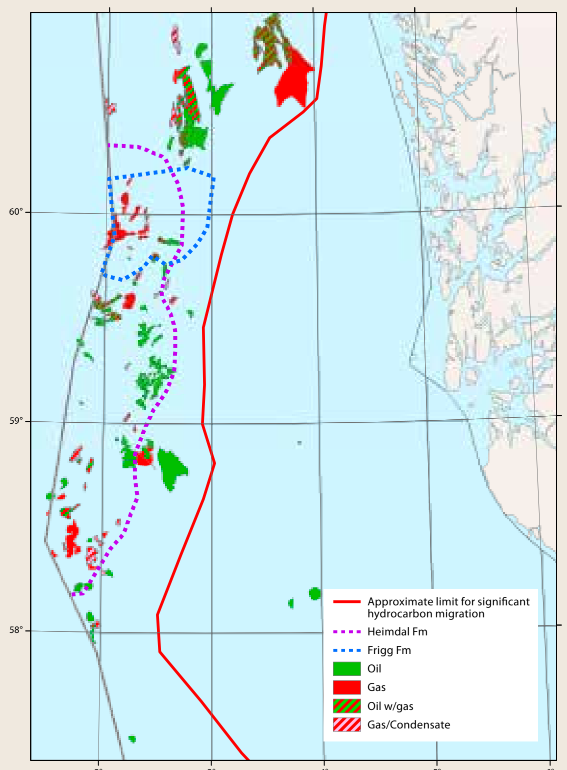
The Sognefjord and Hugin aquifers are hydrostatically pressured to weakly overpressured. The aquifers surrounding the big gas fields have been depleted due to gas production. The Ula Formation has oil fields which are weakly overpressured and relatively deeply buried.

The chalk formations in the southern part of the Norwegian sector have low permeabilities and have not been evaluated for CO_2 storage. The large oil fields have interesting potential for use of CO_2 to enhance the recovery (section 8).

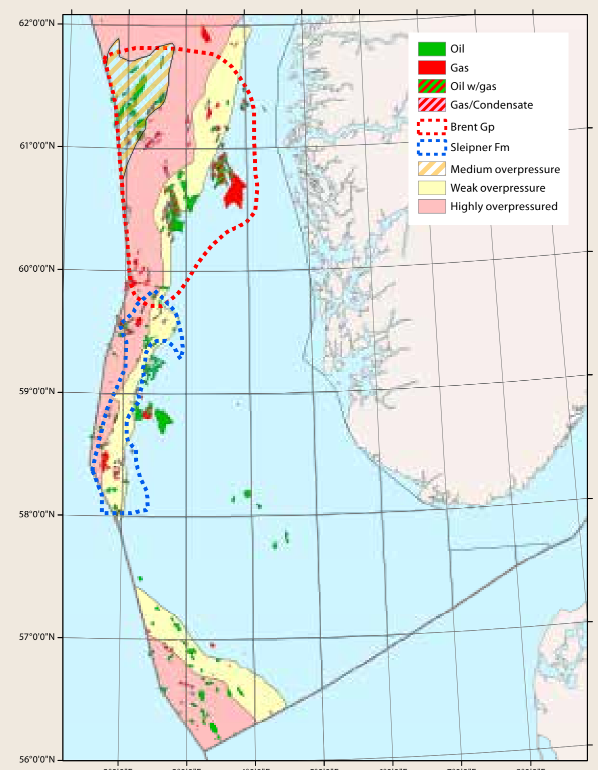
Abandoned fields	Storage capacity, Gt
CO_2 storage in depleted fields	3 Gt
Producing fields	
Close of production in 2030	4 Gt
Close of production in 2050	6 Gt
Storage potensial in the Troll field is not included, expected to be available after 2050.	

The Paleocene and Eocene Ty, Heimdal, Hermod, Balder and Frigg Formations constitute a large hydrostatically pressured aquifer with both oil and gas fields. There is a significant pressure depletion due to gas production in Frigg and Heimdal. The storage potential in the abandoned Frigg Field is presented in the following section.

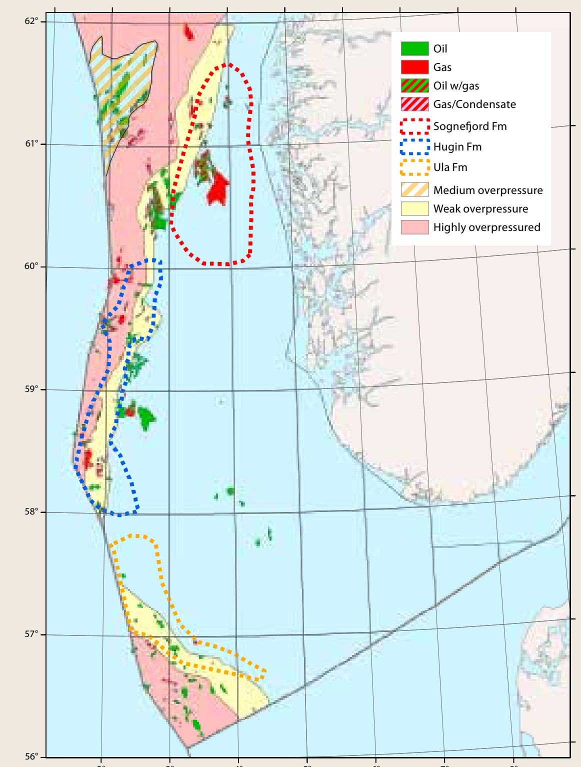
The table shows an evaluation of storage potential in abandoned fields and in today's producing fields, based on close of production year.



Frigg and Heimdal Formations. Hydrostatic pressure/underpressure



Brent Gp and Sleipner Fm, and overpressured areas.



Sognefjord, Hugin and Ula Formations

Lower Jurassic Bridport sandstone, Dorset, England. High porosity, good reservoir quality sandstone with calcite cemented beds and nodules, deposited in a shallow marine environment. The thickness of the sandstone formation in this area is 40-50 m. The Bridport sandstone has been regarded as a reservoir analog for the Sognefjord Formation in the Troll area. Photo: NPD

4.2.2 Abandoned hydrocarbon fields

FRIGG FIELD

The Frigg field was abandoned in 2004 after 27 years of gas production. The field was produced together with Nordøst Frigg, Lille-Frigg, Øst Frigg and Odin, which used the process facilities on Frigg. The field is located approximately 190 km west of Haugesund in Norway. Frigg is a transboundary field between Norway and the UK.

The reservoir consists of unconsolidated sand in the upper part. The properties are generally very good with porosity ranging from 27% to 32% and permeability from 1 to 5 Darcy.

The initial gas pressure was 197.9 bars at 1900 m MSL, and the initial aquifer pressure (Sele/Lista formations) was found to be 223.4 bars at 2191 m MSL. The water depth in the area is about 100 m.

The initial gas in-place volume was 247 GSm^3, of which about 191 GSm^3 has been recovered.

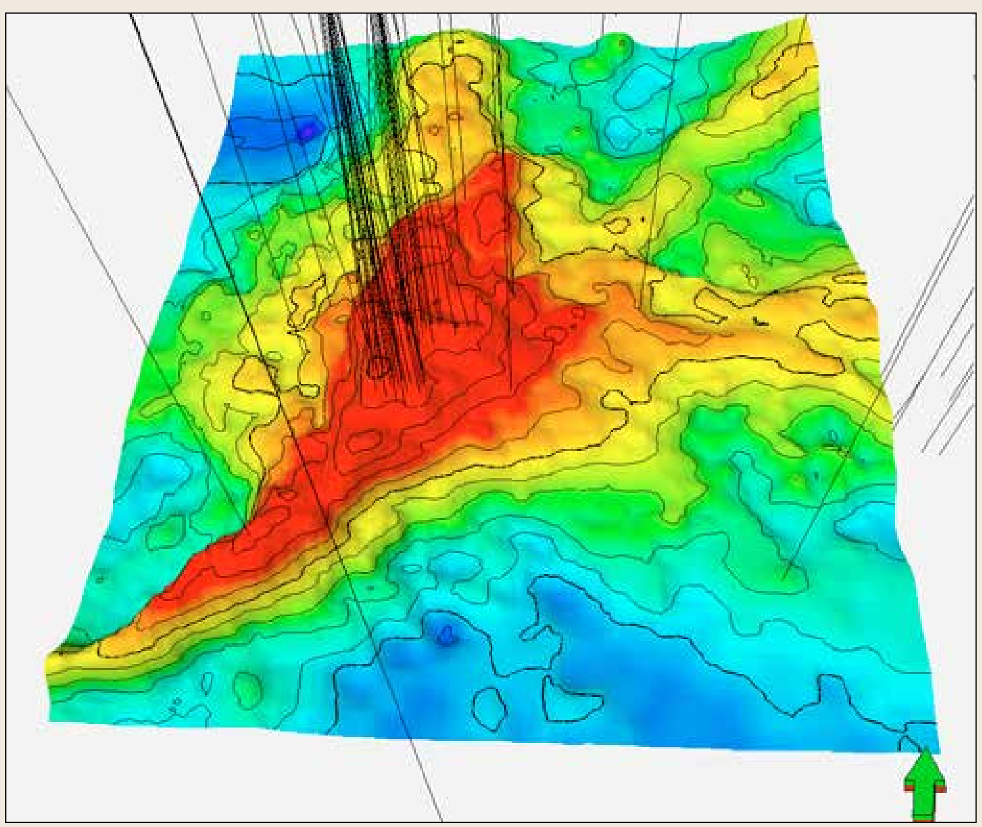
A CO_2 injection study was done by the NPD in 2010 to see if the abandoned field and its satellites might be a candidate for future CO_2 storage. A reservoir simulation model made by Total for the full field was used and converted to an Eclipse E300 compositional model. The model was matched both with regard to PVT and production history. The fluid was described with four component groups: CO_2, N2+C1, C2-C6 and water.

The simulation model included a huge aquifer around the Frigg fields. The model is shown in the lower right figure with grid cells, hydrocarbon accumulation and rock compaction regions. The main cases run were the following:

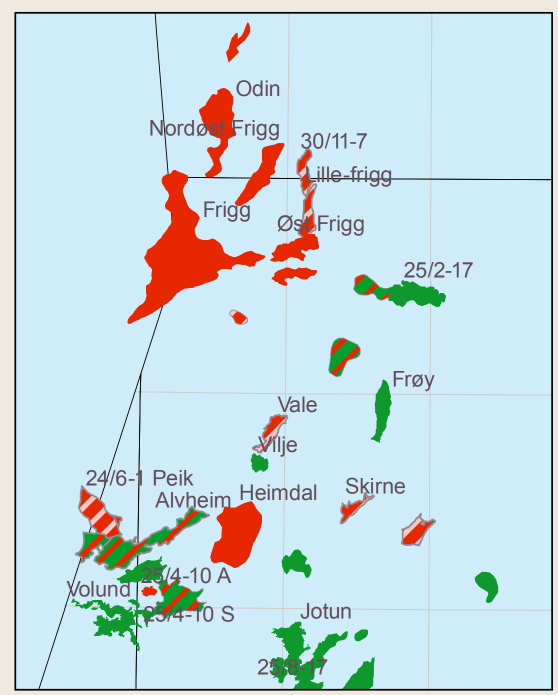
1. Production of remaining gas together with CO_2 injection
2. Injection with closed aquifer, no gas production
3. Injection with leaking aquifer, no gas production.

In case 1, 10 mill Sm^3/d of CO_2 was injected for 55 years from one well in the aquifer, and remaining methane gas was produced from the top of the Frigg field. In cases 2 and 3, CO_2 injection with 10 and 50 mill Sm^3/d was applied in an open aquifer. An open aquifer was simulated by producing water in the corners of the aquifer, thus keeping the pressure increase quite slow. The results are shown in Table 5.2.1. The range in methane gas volume produced is due to the uncertainty in trapped gas saturation, where low values of trapped gas correspond to high volumes produced. Base case trapped gas saturation (Sgr) is 0.28 and gives 0.3 Gsm^3. An Sgr of 0.14 gives 18.8 GSm^3.

In cases 2 and 3, pressure builds up from about 183 bar in Frigg, which is about 20 bars below initial pressure, to 208 bars in case 2 and 278 bars in case 3. The behaviour of CO_2 in the formation water has a long-term effect, as more and more of the free CO_2 will dissolve. This leads to heavier formation water which will start to move downward as shown in the figure.



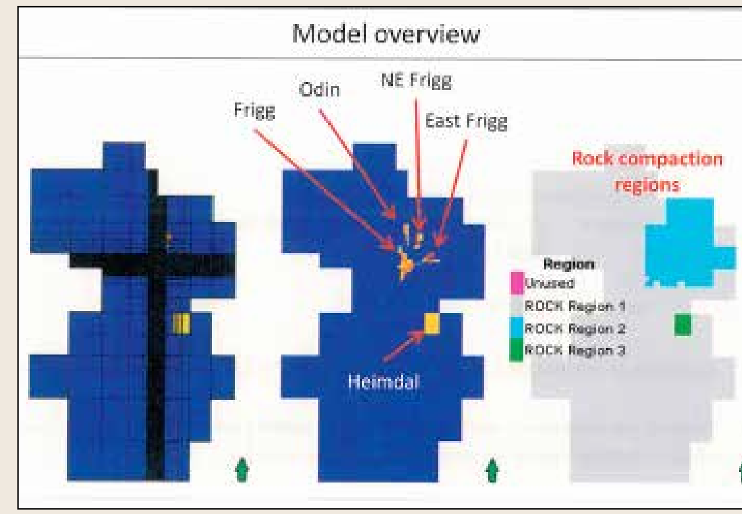
Structural map of the Frigg field with all wells



Frigg field with satellites. Hydrocarbon fields in the Frigg area

4.2.2 Abandoned hydrocarbon fields

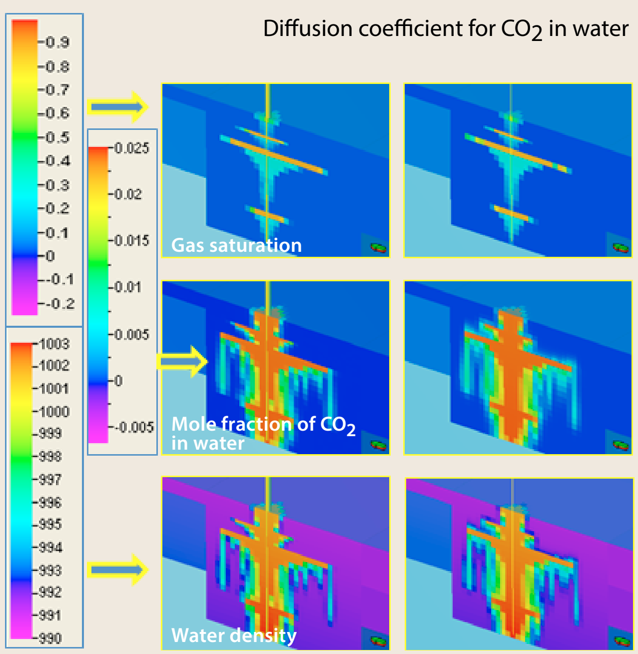
Case	Description	Gas produced, GSm3	Injection period, years	Injection rate	Pressure increase, bar	CO_2 injected Mt	Storage efficiency, % of PV (incl. aquifer)
1	Gas production and CO_2 injection	0.3 – 18.8	55	10		445	0.06
2	Injection in half open aquifer		85	10	25	689	0.09
3	Injection in half open aquifer		85	50	95	3443	0.46
The results show that remaining gas can be produced without CO_2 contamination into the gas.							



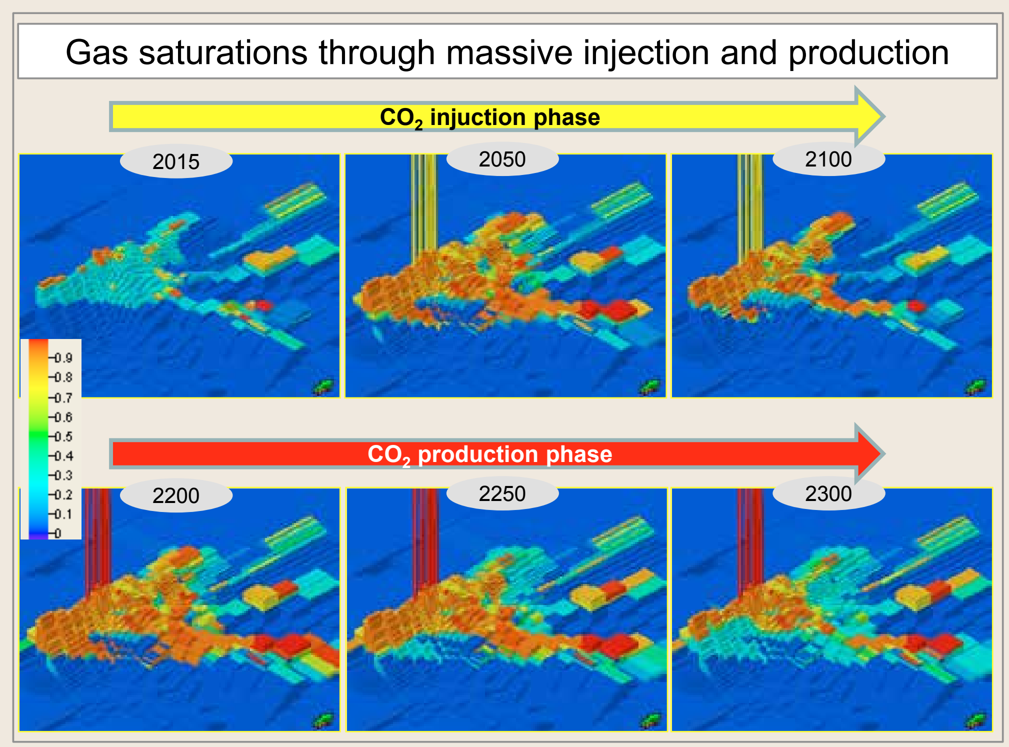
Simulation model

Conclusion
The Frigg field has a large potential for CO_2 storage due to remaining gas in the field itself and a huge aquifer that is connected to the field. The simulation shows that there is a higher potential than what is simulated if the pressure increase is compensated with more water production out of the aquifer.

Some thought should be given to the abandoned wells on the Frigg field and its satellites as their sealing capacity for CO_2 has not been studied in detail. If storage is implemented in Frigg, integrity studies and monitoring of the old wells will be an important issue.



Long term effects of CO_2 injection for two alternative values of diffusion coefficient.



The figure shows the gas saturation during the injection and production. Some of the CO_2 will be trapped behind the waterfront due to relative permeability effects. No diffusion is assumed in this case. 50 MSm^3/d. CO_2 injection during 2015-2100 and reproduction from year 2200 at 5 MSm^3/d.

4.2.3 Summary

The results of the evaluation of theoretical storage capacity in the North Sea are summarized in the tables. Excluding the aquifers in the petroleum systems, two aquifers with significantly greater theoretical storage potential than the others have been identified. These are the Utsira – Skade Formation aquifer and the Bryne – Sandnes Formation aquifer.

The Utsira Formation is already used by the petroleum industry for CO_2 storage. Structures in the Utsira Formation which are equivalent to the site used for the Sleipner injection have been classified within the 3rd level of the maturation pyramid. Only about 25 % of the total pore volume of the Utsira – Skade aquifer has been included in the calculation of storage capacity. The reason is that the top of the aquifer is too shallow to be suitable for CO_2 storage.

The Bryne-Sandnes aquifer has a lower level of maturity than the Utsira formation. In any proposed storage site, reservoir quality and seal integrity must be studied carefully. The aquifer is located in a salt basin, and closed structures formed by salt tectonics may be attractive for CO_2 injection.

The Johansen – Cook Formation aquifer has a smaller pore volume than the two aquifers mentioned above, but it has good reservoir and seal properties. A potential storage site in the Johansen Formation has recently been matured by Gassnova, and is here included in the 3rd step of the pyramid.

In the petroleum provinces, the storage potential was calculated from the extracted volume of hydrocarbons in depleted fields. The main contribution to the present theoretical storage capacity comes from the abandoned Frigg Field and its satellites, which are located in the huge Frigg-Heimdal Formation aquifer. The increase of storage capacity in abandoned fields has been estimated for 2030 and 2050. The storage capacity of that part of the large Sognefjord Delta aquifer which belongs to the Troll Field has been grouped together with the abandoned fields.

CO_2 storage in abandoned and depleted fields will usually require a careful study of the integrity of the wells which have been drilled into the field. If oil has been present, it is relevant to study the potential for enhanced recovery by CO_2 injection. The CO_2 storage potential achieved by potential EOR projects is discussed, but has not been quantified in this study.

Evaluated Aquifers	Avg Depth	Bulk volume	Pore volume	Avg K	Open/closed	Storage eff	Storage Vol	Density in reservoir	Storage Capasity
Unit	*m*	*Gm^3*	*Gm^3*	*mD*		*%*	*GRm^3*	*kg/m^3*	*Gt*
Utsira Formasjon and Skade	1000	2500	530	>1000	Open	4	21	750	15.77
Bryne/Sandnes Formations	1700	5000	440	150	Half open	4.5	20	690	13.60
Sognefjord Delta East	1750	550	110	300	Half open	5.5	5.9	690	4.09
Statfjord Gp East	2400	1100	120	200	Half open	4.5	5.4	660	3.59
Gassum Formation	1700	650	76	450	Half open	5.5	4.2	680	2.85
Farsund Basin	2000	860	82	150	Half open	4	3.3	700	2.30
Johansen and Cook Form.	1700	N/A	91	300	Faults	3	2.7	650	1.78
Fiskebank Formation	1600	100	25	1000	Half open	5.5	1.4	700	0.96
Stord basin, Jurassic model	1450	270	16	5 - 20	Half open	0.8	0.14	710	0.10
Hugin East	1700	19	2	500	Half open	5.5	0.13	700	0.09

Evaluated Prospects	Avg Depth	Bulk volume	Pore volume	Avg K	Open/closed	Storage eff	Storage Vol	Density in reservoir	Storage Capacity
Unit	*m*	*Gm^3*	*Gm^3*	*mD*		*%*	*GRm^3*	*kg/m^3*	*Mt*
Bryne/Sandnes1	1700	13	1.6	150	Open	20	0.32	0.69	220
Bryne/Sandnes2	1700	3.3	0.15	150	Open	20	0.030	0.69	21
Johansen	2900	N/A	N/A	300	Half Open	N/A	N/A	N/A	150
Stord Basin mounds	1900	45	9.7	1000	Closed	0.8	0.078	0.69	53

Total aquifers	Avg Depth	Bulk volume	Pore volume	Avg K	Open/closed
Unit	*m*	*Gm^3*	*Gm^3*	*mD*	
Utsira total	1000	8500	1800	>1000	Open
Sognefjorddelta total	1750	2700	480	300	Half open

Abandoned and producing Fields	Storage Capacity Gt
Abandoned fields	3
Producing fields	
Close of production within 2030	4
Close of production within 2050	6

4.2.3 Summary

Storage capacity in Gt and technical maturity

Aquifers

Basin/reservoir	Storage capacity	Maturity		
	Total	Blue	Green	Yellow
Utsira and Skade	15.8		14.8	1
Bryne/Sandnes southern parts	13.6		13.6	
Sognefjord Delta East	4.1		4.1	
Statfjord Gp East	3.6		3.6	
Gassum	2.9	2.9		
Bryne/Sandnes Farsund basin	2.3		2.3	
Johansen and Cook	1.8		1.7	0.1
Fiskebank	1	1		
Hugin East	0.1		0.1	
Stord basin, Jura	0.1	0.1		
Stord basin , mounds	0.05	0.05		

Field related

		Blue	Green	Yellow
Abandoned fields	3		3	
Fields in production 2030	4		4	
2050	6		6	
Sognefjord delta including Troll	14		14