DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/44**

Capture, Storage and Use of CO_2 (CCUS)

3D static reservoir model of the Havnsø structure (Part of Work package 6 in the CCUS project)

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
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Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO_2 capture technologies, (2) the potentials for both temporary and permanent storage of CO_2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO_2 usage potentials, including business case for converting CO_2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1–2 large-scale demonstration plants in Denmark.

The present report forms part of Work package 6 and focuses on producing a numerical 3D reservoir model of the Gassum Formation, which is to be used further in the analyses of dynamic capacity and injectivity.

Contents

Dansk sammendrag

Til brug for den efterfølgende dynamiske reservoir analyse af Gassum Formationen i Havnsø strukturen af bl.a. kapacitet og injektivitet er der konstrueret en 3D reservoirmodel. Den opbygges fra en strukturel model som anvender den eksisterende kortlægning til at afgrænse model volumenet, og tilføjes indhold i et regulært netværk som afspejler arkitekturen og den rumlige fordeling af sandlegemer og porøsitetsværdier.

Afgrænsningen af toppen af reservoiret udgøres af det forud eksisterende kort over toppen af Gassum Formationen, idet den nyeste kortlægning er foregået forskudt for model arbejdet og ikke er blevet indarbejdet. Det betyder også at væsentlige elementer i en reservoirmodel, f.eks. mulige forkastninger, ikke er beskrevet i det anvendte kort som er baseret på et mangelfuldt data grundlag.

Den interne arkitektur og fordelingen af sandlegemer og porøsiteter bygger ligeledes på et manglende data grundlag, idet Havnsø strukturen ikke har boringer til at oplyse om disse forhold. Geometrierne og porøsitetsfordelingerne er derfor kun konceptuelle, og er baseret på formodningen om en analogi hentet fra tolkningerne udført i den mere velundersøgte Stenlille struktur ca. 30 km sydøst for Havnsø.

For at afspejle nogle af usikkerhederne i den konceptuelle fremstilling er der udarbejdet et sæt scenarier med forskellige geometrier og fordelinger, som vil blive undersøgt i den dynamiske reservoiranalyse.

Den leverede reservoir model skal betragtes som en version 0, idet ingen lokale data med tilstrækkelig informationsindhold er indbygget. Integration af de nyeste tolkninger på de eksisterende data vil bidrage til en relevant opdatering, men en afgørende øgning af sikkerheden i modellen er betinget af ny indhentede seismiske data og en boring som kan tilføje lokal og detaljeret viden om geometrier og indhold.

Summary

As preparation for the dynamic reservoir analysis, a 3D static model with properties for facies and effective porosity is produced for the Havnsø structure – a potential site for CO_2 storage. The structure is not drilled, and the seismic data as well as the coverage are of mediocre quality. Therefore, analogue concepts from the Stenlille structure have been used for facies and porosity patterns, and some of the uncertainties are reflected via different scenarios.

The geological model and the interpretations of the depositional environments deliver the basis for deciding the best method in the reservoir modelling to reflect relevant patterns and architecture of the reservoir. The geological model is mainly based on interpretations on the dataset from the Stenlille structure considered to be a close analogue, supplemented with information from regional structural data and from other wells in the region penetrating the Gassum Formation.

Based on the geological model and the interpretations of the depositional environments and thereby of the size, shape, and overall architecture of porous sedimentary bodies, the modelling methods have been designed to reflect all this by a combination of facies modelling and subsequent petrophysical property modelling.

The presented reservoir model should be regarded as a version 0 model, since no local data with sufficient information are incorporated. The integration of the most recent interpretations reported in other parts of this project will support an important update, but a decisive improvement with increased reliability of the model is depending on new data from seismic investigations and drilling of a well, supplying local and detailed data on geometries and properties.

Introduction

In the context of the present CCUS 2020 project it is important to keep in mind that the current investigations supplying additional data and new information for designing advanced reservoir models of both the Havnsø and the Hanstholm structures have been performed in parallel to the modelling activity. Therefore, the present model versions have incorporated only limited new input and are mainly based mainly on existing data and interpretations. The most important aspect is that the work reported here shows the full chain of data analyses, data input, model design, uncertainty treatment etc. as well as transfer to dynamic investigations with injection simulation; all steps being necessary for contributing to a valid assessment of a storage complex. The present version_0 will be updated to a version_1 based on the expected future planned integration of the delivered results from the seismic, stratigraphic and petrophysical studies (reported from the various project teams). In the event that newly acquired seismic and well data will be available in the future it will be mandatory to update to a version_2.

The importance and relevance of producing this version_0 model is primarily to establish the work flow and that the model building competencies are in place, and also for the constructed reservoir model to serve as a tool for illustrating the 3D architecture of a storage formation to serve as an educating element and inspiration for improvements.

Previous work

The informal name Havnsø structure is used for an on- and offshore domal closure at Gassum Formation level situated approximately 15 km northeast of the city of Kalundborg (Fig. 1). Approximately 1/3 of the structure is situated offshore, with the top point situated onshore.

The first estimate of storage capacity for the Havnsø structure was published from the EU 5th Framework Programme project GESTCO (2000–2003) (Larsen et al., 2003). It was based on the existing maps and data extracted from wells in the surrounding area for average porosity, Net/gross, Reservoir thickness of the Gassum Formation, and a storage efficiency factor derived from studies in other projects (Holloway et al. 1996). The map for the Top Gassum Formation was based on the limited seismic data available at that time. The structure itself is not drilled, and the reservoir thickness estimate is therefore very uncertain. A study of dynamic filling of the structure by reservoir simulation is presented by Bech (2003) and Bech & Larsen (2005) generally following the principles applied in the case study on another reservoir type published by Bech & Frykman (2002).

Seismic data and map material

The map for the Top Gassum surface at Havnsø is fairly uncertain due to limited seismic data at the time when the map was produced. (File used: Top_UnitE2_Gassum_Depth-anm.DAT).

The Top Gassum Map from the regional 2D seismic mapping has been imported into Petrel. Uniform thickness of 150 m in the reservoir within the model area has been assumed, corresponding to the approximate maximum thickness in the nearby Stenlille structure. No faults are included in the gridding of the 3D model, as the existing map has no information on such structural features due to limited data.

The Gassum reservoir is subdivided into a number of zones in the Stenlille area, mainly based on correlating the sandstone units and defining zones that have relevance for the operation of the gas storage facility (GSD 2018). A new subdivision based on sequence stratigraphic principles is in preparation, and to a large extent resembles the previous reservoir zonation. The present model does not incorporate any subdivision into zones within the Gassum Formation, since there is no well information to guide any additional surfaces in the Havnsø structural model.

In future updates the most porous zones can be gridded more finely vertically than the less porous intervals. This is to secure the best reflection of the CO_2 migration in the high permeable layers.

Guided by the deepest closing contour, a model area was decided with size 16x20 km (Fig. 1).

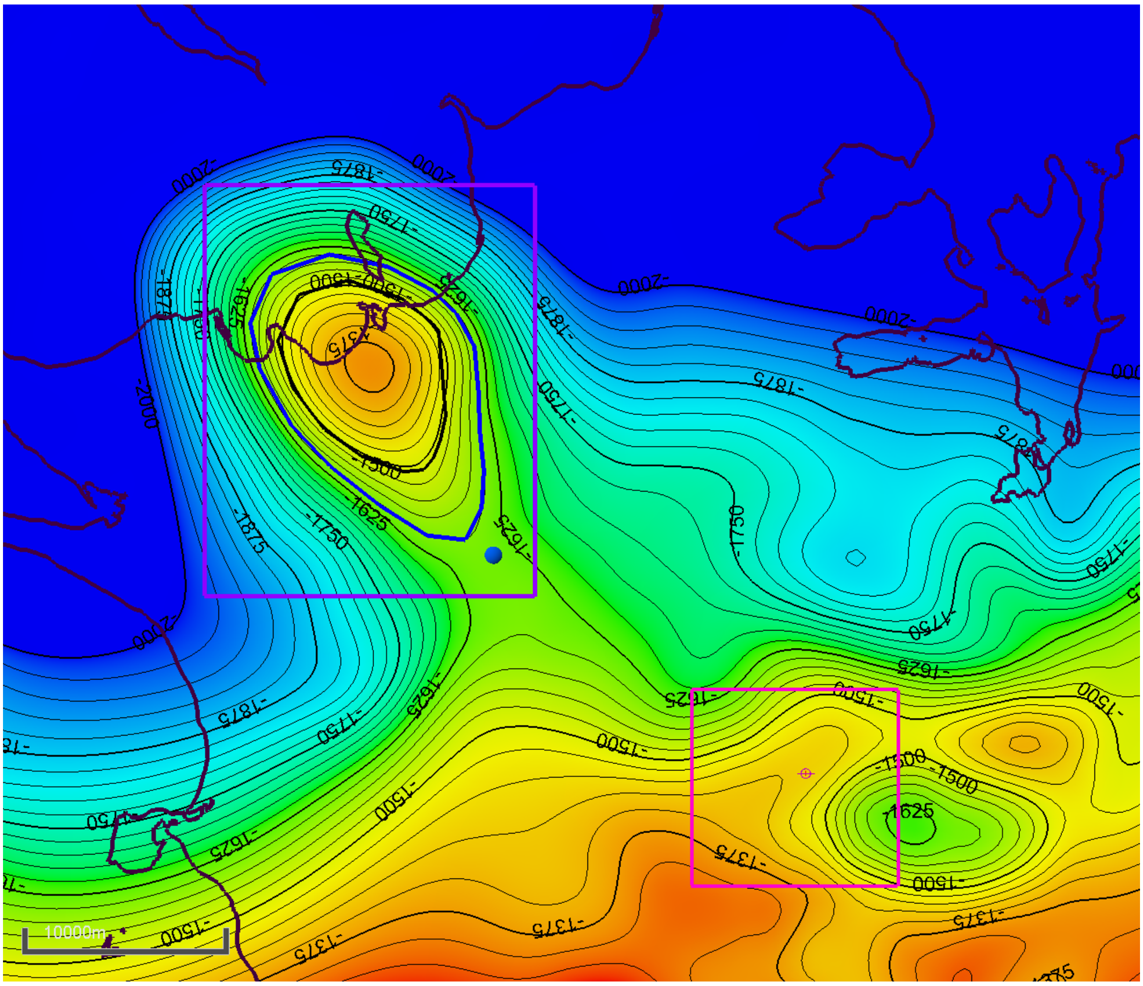

Figure 1. Map showing the Top Gassum surface in the region of Havnsø and Stenlille with model size indicated for Havnsø with purple box. Stenlille area in red box. Scale bar is 10 km.

Well data

Until now (2020) no wells have been drilled on the Havnsø structure. The closest location for well information is 30 km to the SE from the Stenlille structure. Therefore, both data derived from the Stenlille wells and interpretations of the depositional environments are regarded as analogue material that has been transferred to the Havnsø area.

Well database and data quality

The 20 Stenlille wells have been drilled over a period of 2006–2017, and well logs of varying type and quality are available, as well as core material from certain sections.

The Stenlille structure with a total of 20 wells have 6 deviated wells out of the 19 reaching into the reservoir. The ST-3 well has TD above the reservoir and is used for monitoring purposes in a sandstone layer in the overlying seal formation of the Fjerritslev Fm.

The succession at Stenlille is illustrated by the Stenlille-1 well (Fig. 2). The seal of the Stenlille aquifer is approximately 300 m of mudstone of the Fjerritslev Formation. The formation has proven tight as seal for the gas storage since 1991.

In the context of storing CO_2 the overlying very thick chalk group forms a secondary caprock with its low permeability and reactivity potential.

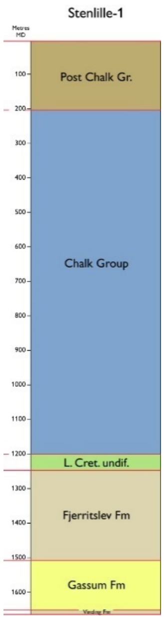

Figure 2. Stratigraphic depth section of the Stenlille-1 well showing the lithostratigraphic units and their thickness. The main reservoir is sandstones of the Gassum Formation. The lithostratigraphic units and definition of formation boundaries in the deep wells are based on Nielsen & Japsen (1991).

Porosity calculations

The Stenlille wells have been reviewed for interpretations of lithology and porosity. The interpretation of the clay content (shale volume) is based on the gamma ray log, and the porosity is calculated from the neutron-density logs combined with the shale volume estimate. The effective porosity estimates are truncated at a maximum value of 25% in order to avoid artefacts, and the relation to other porosity data is discussed later.

The lithology classification has used sandstone/shale as the two main categories, and the separation is made at a threshold in the calculated Vshale parameter derived from the gamma logs.

The porosity log has been generated for each well as an effective porosity (PHIE). The PHIE result is chosen for incorporation in the model since the following flow simulation only treats the mobile water for simulating the replacement of water with the injected CO_2.

Construction of well log input for pseudo-well

The amount of sandstones, given by the Net/Gross ratio in the different Stenlille wells, is variable and ranges from below 50% to more than 90%. In order to study this uncertainty a representative for each extreme has been selected and used as input for the modelling of the Havnsø reservoir model. In this case the ST-5 and ST-2 sand/shale succession and the porosity distribution has been transferred to the Havnsø structure as pseudo-wells for the conditioning of the model.

The pseudo-well HS-5 is based on ST-5 having one of the lowest sandstone occurrences in Stenlille. The sand lithology is renamed to FACIES since that is the term used in the modelling procedure.
The thickness of the Gassum Fm is only 144 m in the ST-5 well, and therefore the lowermost 6 m in the used pseudo-well is posted as shale, since that will not influence the modelling of the upper part where the main flow will occur (fig. 3).

The pseudo-well HS-2 is based on ST-2 having one of the highest sandstone occurrences in Stenlille. The sand lithology is renamed to FACIES since that is the term used in the modelling. The thickness of the Gassum Fm is only 142 m in the ST-2 well, and therefore the lowermost 8 m in the pseudo-well is posted as shale as described above.

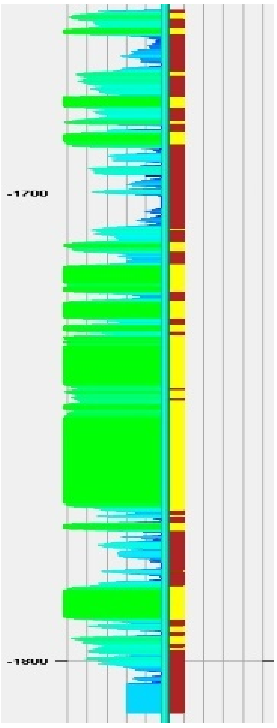

Figure 3. Illustration of the well HS-5 with PHIE porosity log (left track, truncated at max value 25%) and the Facies track (right) with mudstone=shale (brown) and sandstone (yellow).

Core material and petrophysics

Core material is available from several of the Stenlille wells in different positions in the reservoir, however mainly from the upper part of the Gassum Fm. The core material has provided samples for the petrophysical investigations.

Porosity and permeability correlations

Conventional core analyses are extracted from reports from various laboratories (GEUS, COREX etc.). Most of the analyses are gas permeabilities, which is then converted to fluid permeabilities prior to the flow simulation. In the porosity-permeability relation (Fig. 4) the upper and lower sandstones seem to form separated populations and might be used for a different implementation for the two parts in the reservoir model.

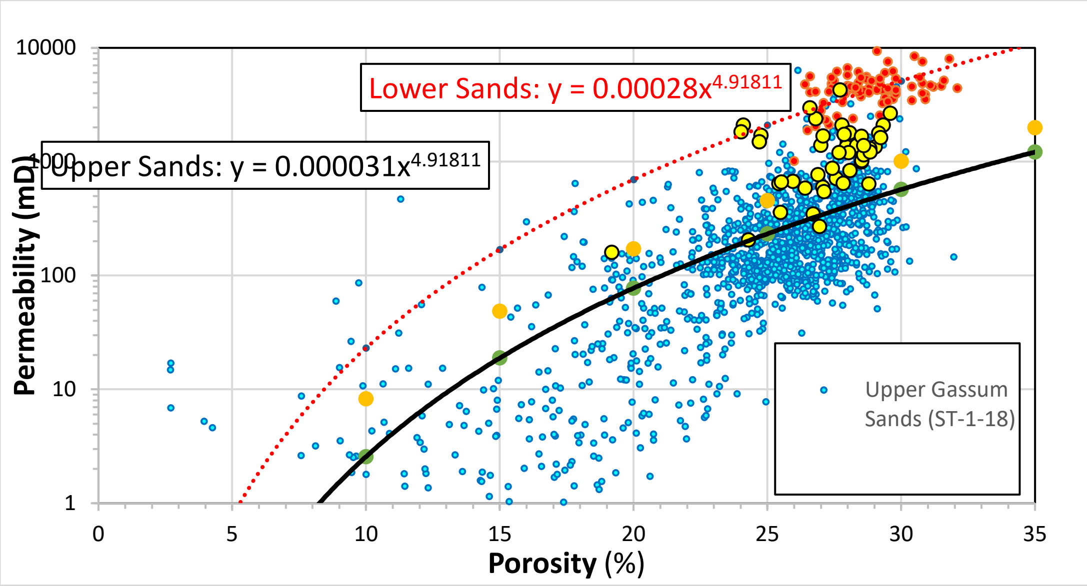

Figure 4: Porosity-permeability relationships for the Gassum Formation sandstones, based on conventional core analysis data from cored Stenlille wells. The black line represents a trend for the upper part of the Gassum Formation, the red dotted line represents the lower part of the Gassum Formation. Permeability values are gas permeabilities measured in a core laboratory (GEUS, COREX etc.). The orange points refer to the GEUS porosity-permeability correlation model representing the Gassum Formation outside Stenlille (included for comparison).

Reservoir model

The position for the pseudo-well is chosen in the SE corner of the model area (Fig. 5) which is onshore and placed away from the probable injection well which could be situated in the SW about 8 km distance from the Kalundborg deep-water harbour from where the CO_2 potentially could be delivered via pipeline. The pseudo-well is also a potential monitoring option since it is placed in the spill point corridor.

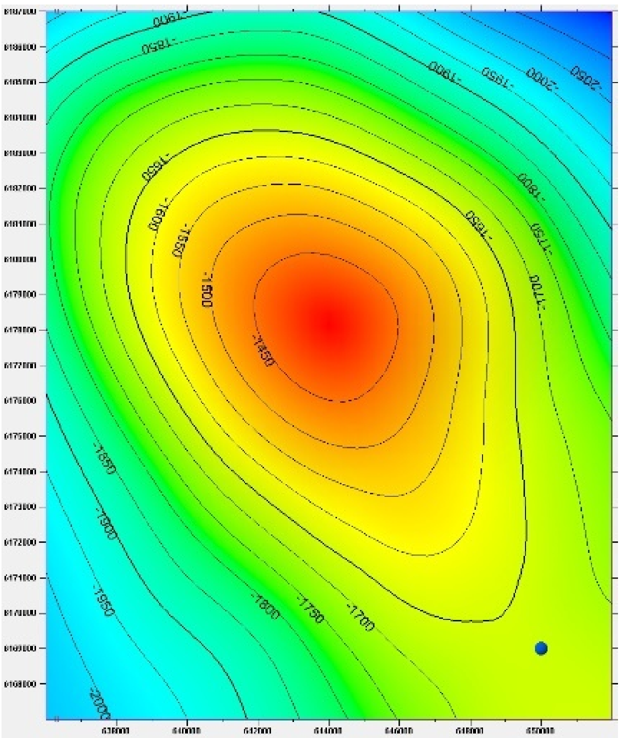

Figure 5. Depth map for the top Gassum Fm in the model area (TVDSS m). The wellhead is placed at UTM 650000, 6169000. For simplicity KB=0. The well penetrates the Top Gassum horizon at 1661.40 m TVDSS. The structure has its apex at 1410 m TVDSS.

Design of reservoir model

The primary input for the reservoir model is the Top Gassum map which is imported in Petrel (v2017). The map is copied for use as the bottom reservoir. A uniform thickness of 150 m is used for the Gassum reservoir model. The caprock thickness is not considered since that will be installed in the subsequent reservoir flow simulation pre-treatment, but we assume the true thickness of the caprock is around 300 m.

The top and bottom maps are installed as model horizons in a regular grid with areal cells of 100x100 m and 1 m thick cells in the reservoir.

The local information in the pseudo-well on Facies and porosity PHIE is upscaled into the model grid. For the facies is used “most of” criterion, and for the porosity simple averaging on the well data which is given in 0.15 m increments.

The model workflow involves as the two first steps an object model overlain with a petrophysical model. The object model is using bodies of elongated ellipses for both sandstone and shale, where the sizes and shapes can be adjusted to the concepts from the geological model for the depositional facies. The ellipses for the shale layers are designed to be more continuous than the sandstone bodies.

The total sandstone proportion = Net/Gross = N/G is modelled from the well data, and as a guide for the reservoir stratification we assign a smoothed vertical proportion curve (VPC) to guide the vertical distribution of sand/shale bodies. The VPC is based on the pseudo-well information, and therefore the layering in the well is propagated into the whole model volume.

For the petrophysical model of the spatial distribution of effective porosity PHIE is chosen the method of Gaussian random function simulation, fairly similar to the standard sequential Gaussian simulation (SGS).

Specification of the depositional control

For scenarios for the total sandstone proportions in the reservoir we select the two extremes known from the Stenlille wells of 50% to 90%.

For both those N/G sets we choose two directionality scenarios for the elongation of the sedimentary bodies with directions along NNW–SSE and ENE–WSW, respectively.

This is inspired by the suggested depositional pattern for the nearshore and shoreface sandy deposits and the deeper shelf shale sheets deposited during transgressive intervals. The two directions are intended to reflect possible coastline orientations as illustrated in Fig. 6.

Figure 6. Tentative illustration of how the paleogeography may have looked at a certain time during deposition of the Gassum Fm. The green area is assumed land area with rivers running towards the marine area (blue). The Havnsø region is situated just below the center of the map.

Scenario set 1 – low N/G

Low N/G, HS-5 well, coastal facies and shelf mud, elongation NNW, named 1A_NNW5

Low N/G, HS-5 well, coastal facies and shelf mud, elongation ENE, named 1B_ENE5

Scenario set 2 – high N/G

High N/G, HS-2 well, coastal facies and shelf mud, elongation NNW, named 2A_NNW2

High N/G, HS-2 well, coastal facies and shelf mud, elongation NNW, named 2B_ENE2

Input definition for object models

The Property modelling/Facies input panels are used to describe body shape, size, directionality (Figs 7–10), and the resulting models are illustrated (Figs 11–13).

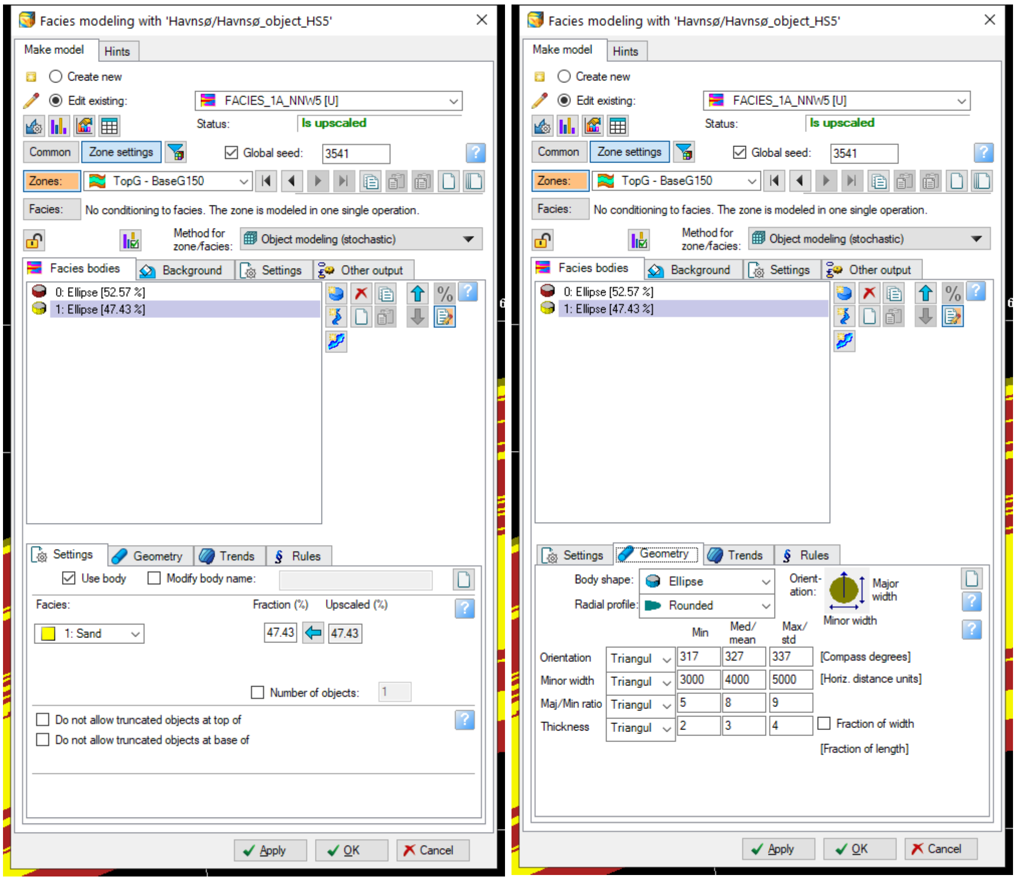

Figure 7. Sand body input parameters. Scenario 1A, Low N/G, HS-5 well, coastal facies and shelf mud, elongation NNW

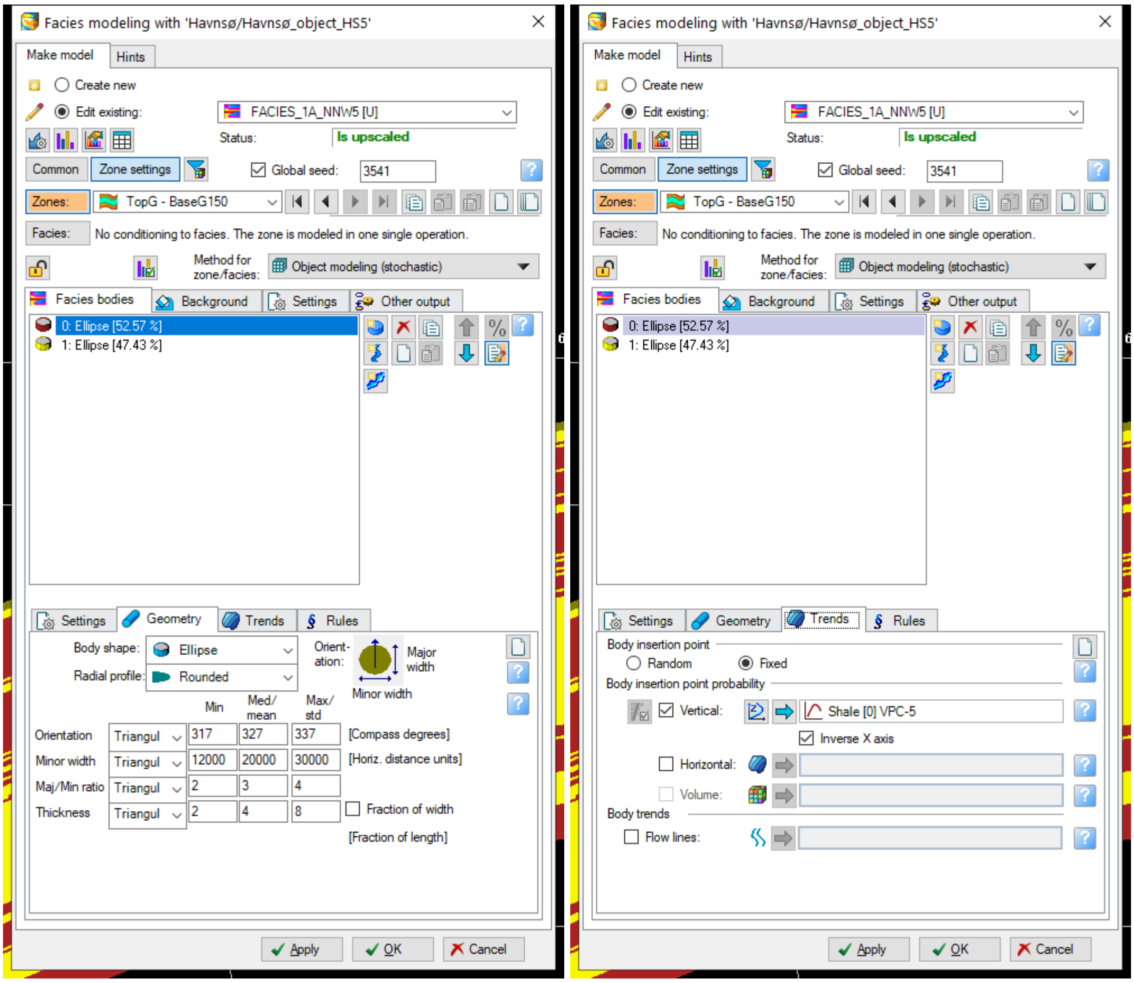

Figure 8. Shale body input parameters. Scenario 1A, Low N/G, HS-5 well, coastal facies and shelf mud, elongation NNW. The stratification is guided by the vertical proportion curve (VPC) for the shale facies.

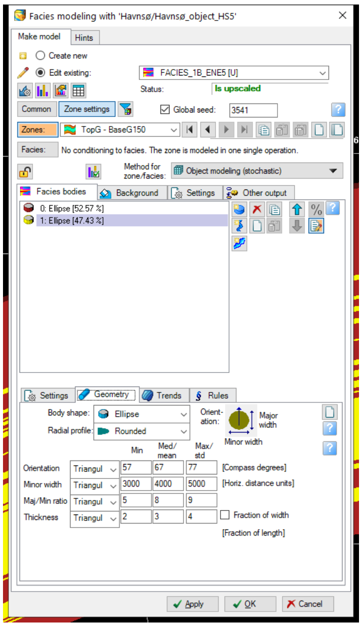

Figure 9. Scenario 1B. Direction input parameters, all other setting as in 1A.

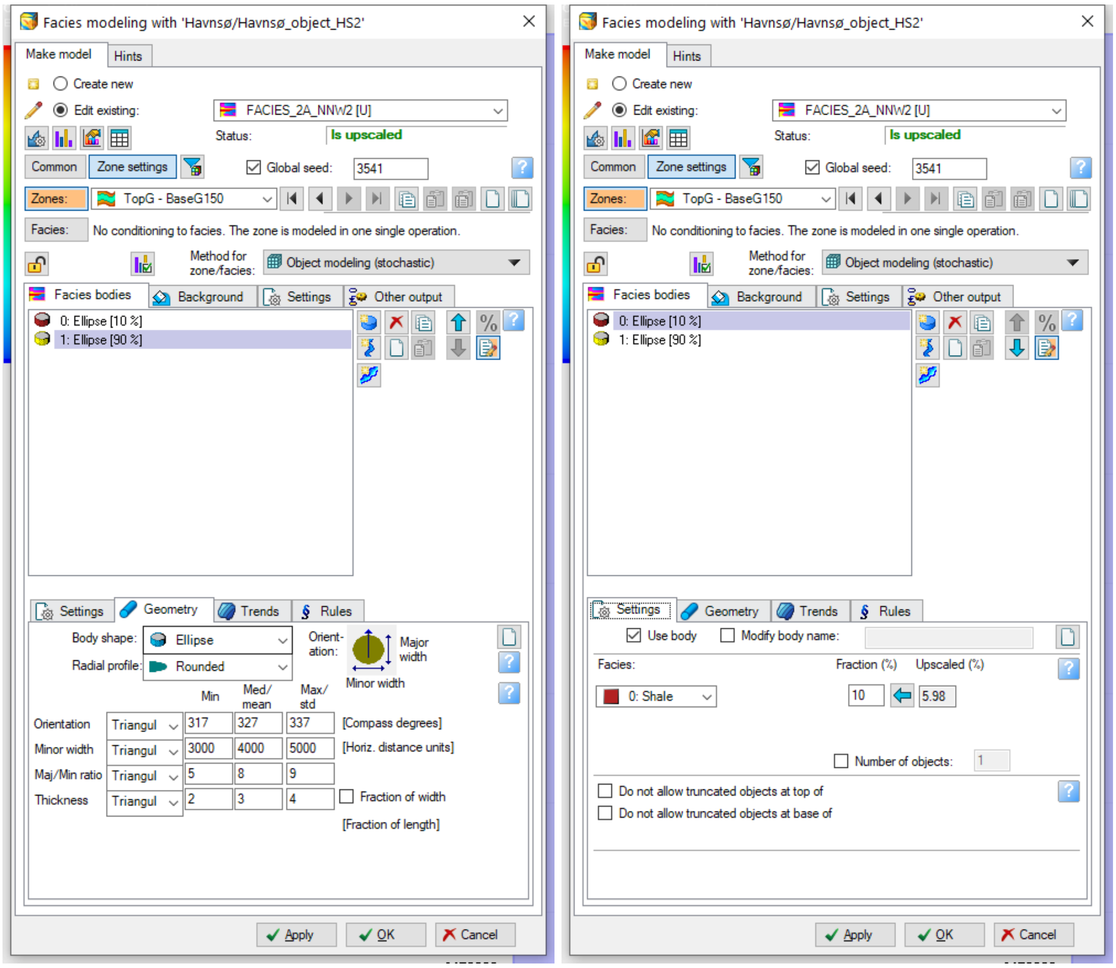

Figure 10. Input parameters adapted for the high N/G Scenario 2A, HS-2 well. The N/G is forced to 90%, modifying slightly the well information on N/G.

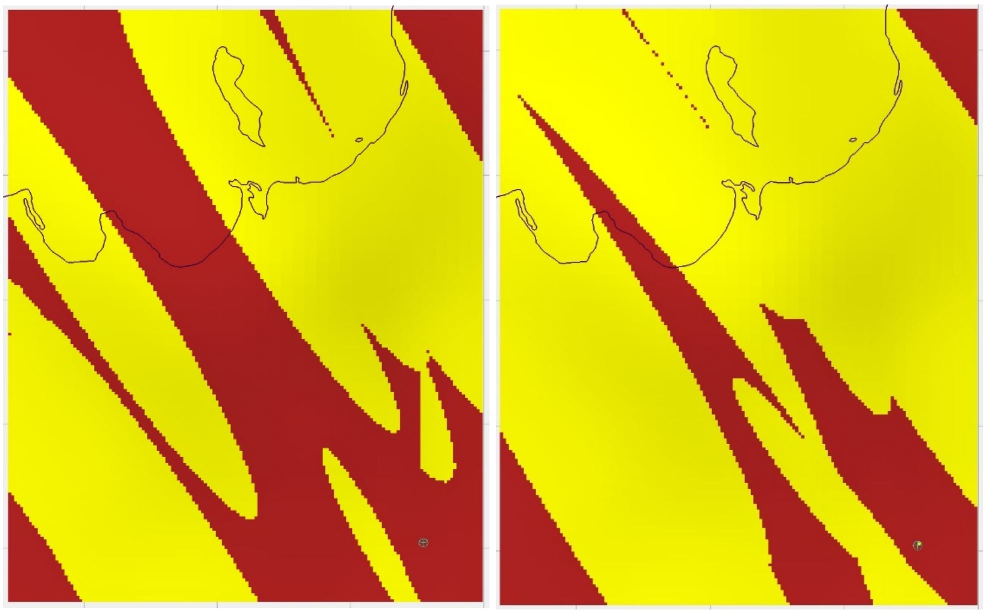

Figure 11. Layer 65 in facies model for scenario 1A and 2A showing the desired difference in the proportion of the sand.

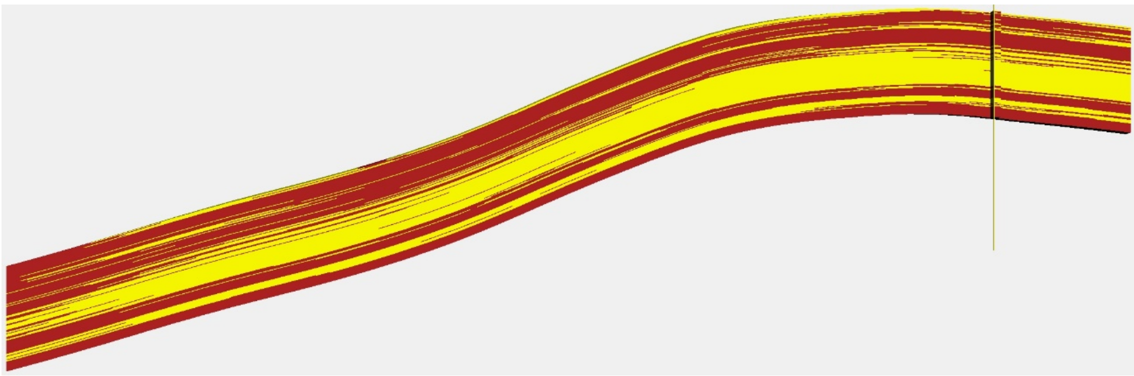

Figure 12. EW section in facies model low N/G scenario 1A through the well.

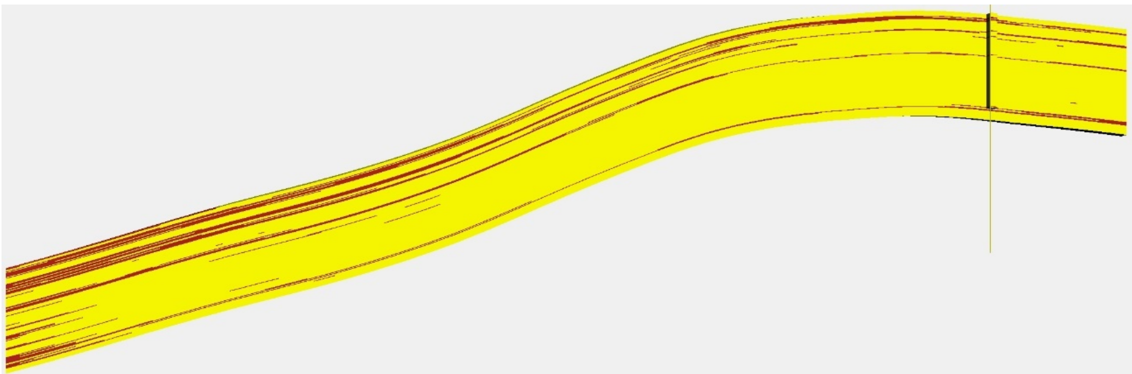

Figure 13. EW section in facies model scenario high N/G 2A through the well.

Input definition for petrophysical models

For modelling the porosity, the input is specific for the two different facies sandstone and shale. The target distributions (histograms) and variograms are the main input for simulating porosity overlain onto the modelled facies.

From the well data in HS-5 we generate the two histograms (Fig. 14).

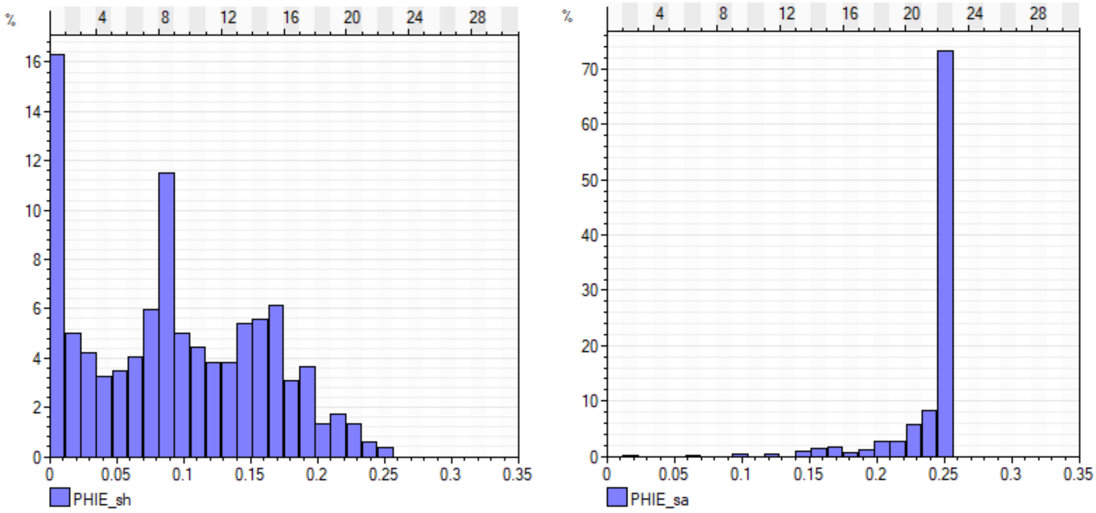

Figure 14. Histogram of well data for shale and sandstone in HS-5.

It is noted that especially the shale lithology has a large overlap with the sandstone population. This can be explained by the thresholding at a certain clay content estimate (Shale volume), allowing heterolithic intervals to be classified as shale even if they include some sandy layers, which increases the porosity estimate when interpreting the well log data.

The upscaling of the well data modifies the distributions slightly in that the thin layers in the well log data are eliminated in the averaging (Fig. 15)

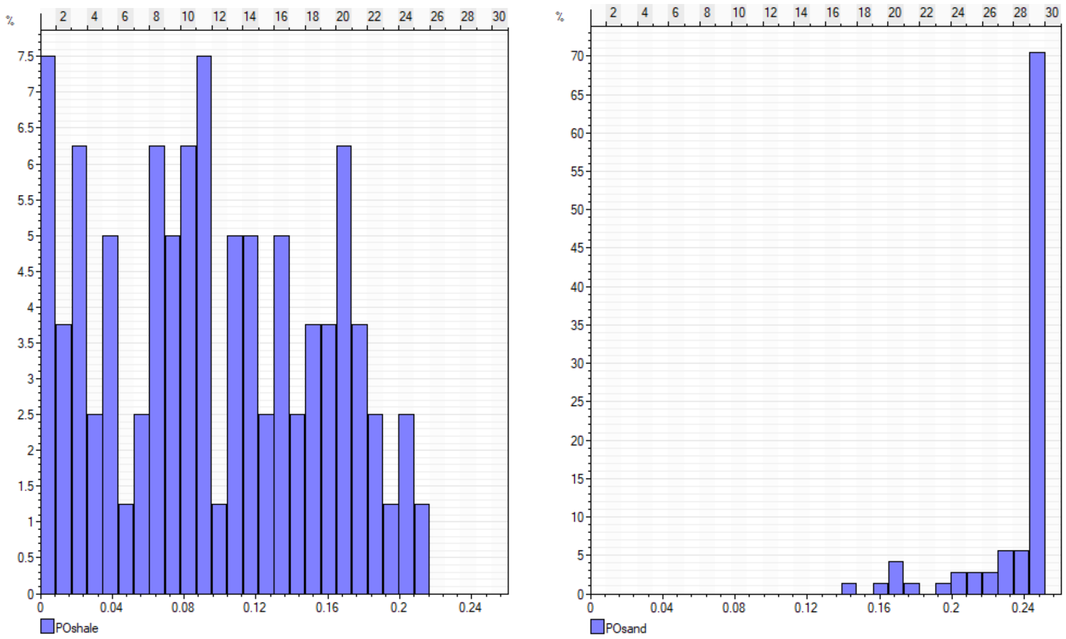

Figure 15. Histograms for the upscaled porosity data for shale and sandstone.

Since the porosity data from the core analyses reaches up to 32% porosity it is clear from this analysis that the 25% limit in the interpreted porosity data might not be fully representative of the true porosity distribution. Since some of the sandy units are assumed to be fairly homogeneous, the target histogram for porosity modelling has been extended up to 32% as the maximum value and minimum value of 12%, and the target histogram for shale porosity has been narrowed to 9–12%. The effect in the simulation is shown in Fig. 16.

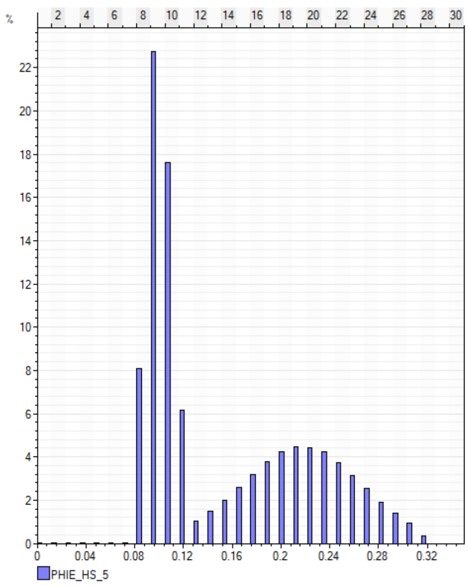

Figure 16. Histogram of simulated porosity distribution in scenario 1A illustrating the two populations for the sandstone and shale porosity.

The input used for the Gaussian Random Function model is describing both a target histogram for each lithology and size description by the variograms including directionality of elongated porosity regions within each of the facies simulated in the previous step (Figs 17-19).

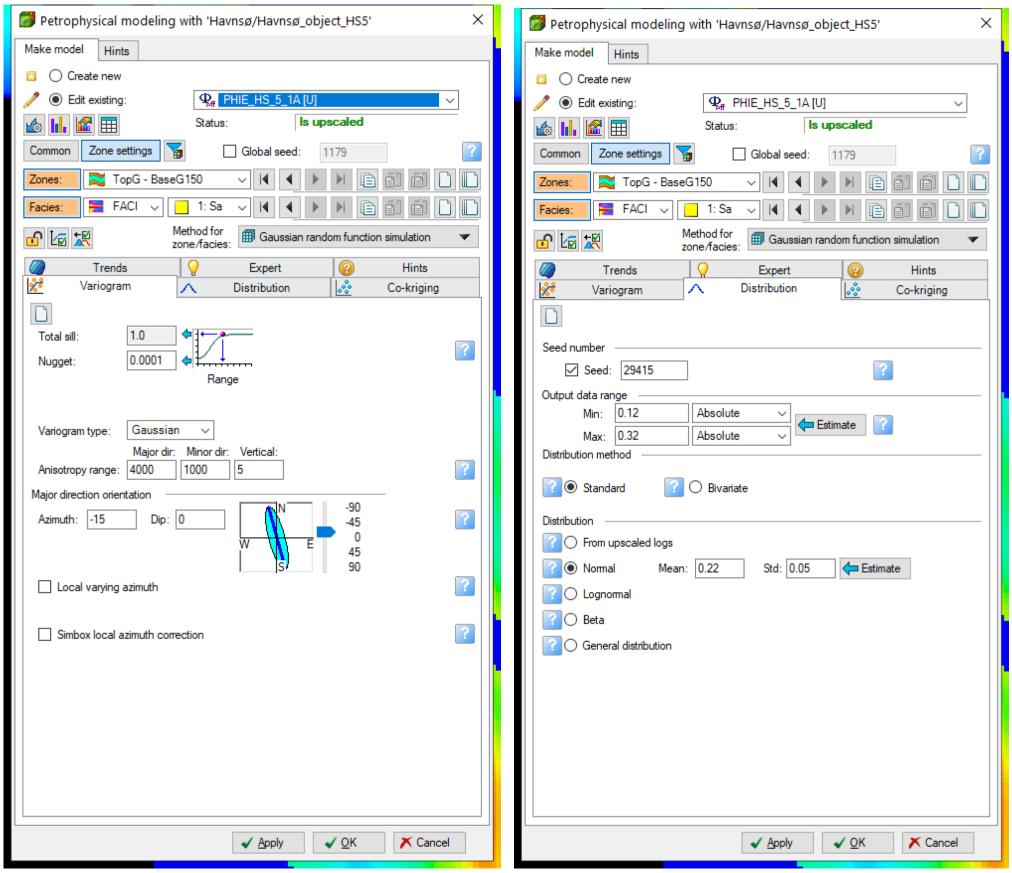

Figure 17. Input sheets for the sandstone porosity distribution and geometry in scenario 1A, low N/G.

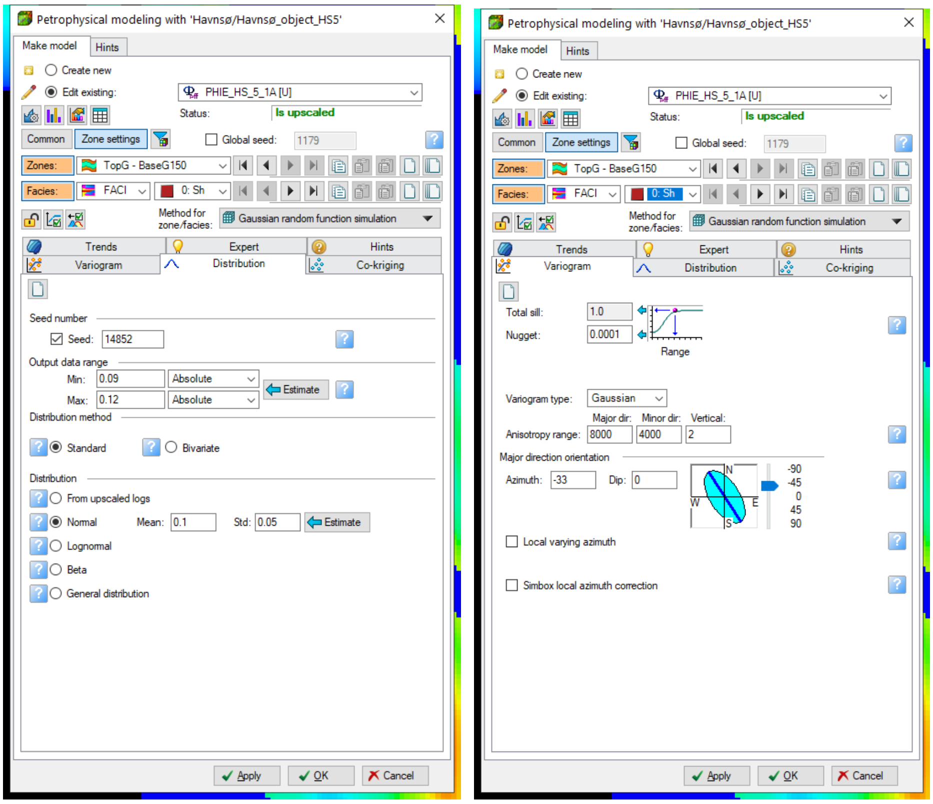

Figure 18. Input sheets for the shale porosity distribution and geometry in scenario 1A, low N/G.

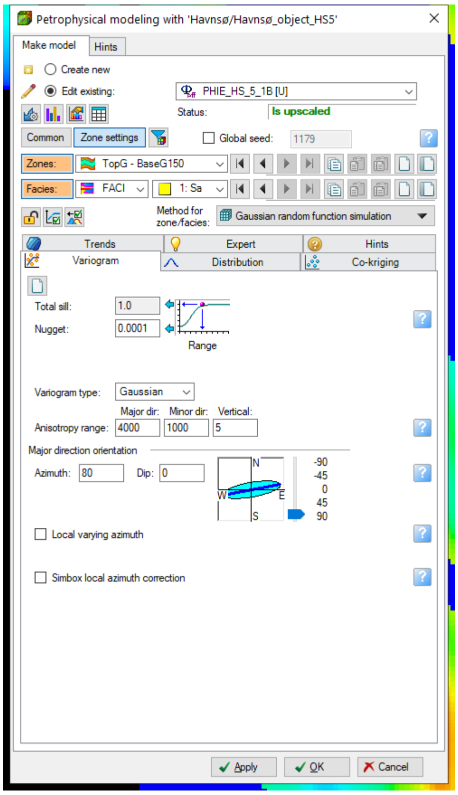

Figure 19. Input sheet for the shale geometry in scenario 1B, low N/G with the NNE directionality.

Directionality of porous sand bodies

Within the sandstone facies we have imposed a direction for the porosity distribution with an angle of 15–20 degrees oblique to the facies belts (Fig. 20). This is inspired by the mapping of shoreface attached sand ridges as shown by Hapke et al. 2016 obtained from Schwab et al. 2013 (Fig. 21).

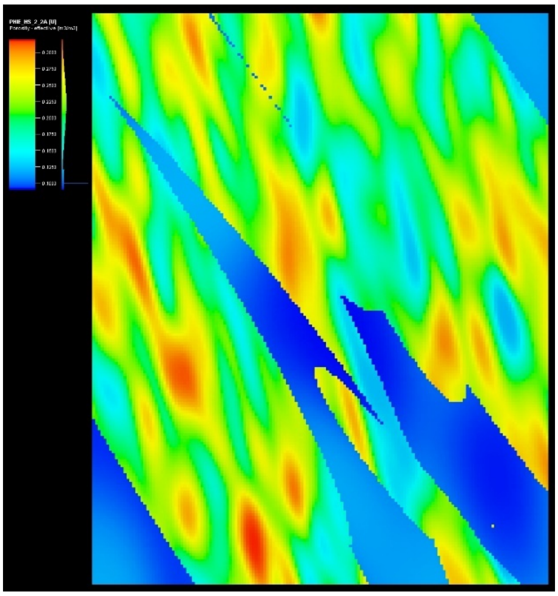

Figure 20. Porosity distribution in model 1A (low N/G) showing the oblique porosity extent in relation to sandstone facies main direction.

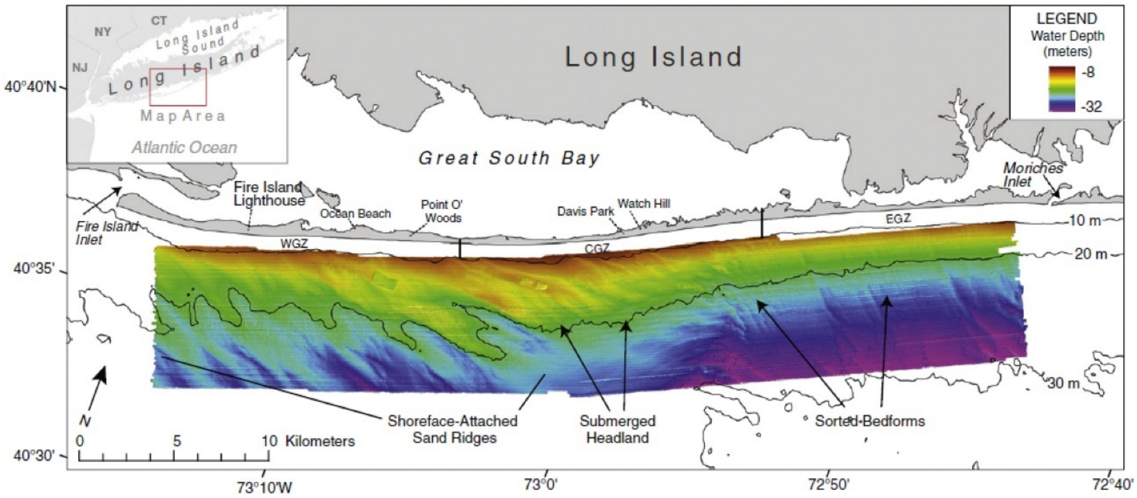

Figure 21. An example of a nearshore sand depositional system with a barrier island and shoreface attached sand ridges. The example is from a mapping of Fire Island which is part of the barrier island system that flanks the south shore of Long Island, New York. (From Hapke et al 2016).

The directionality of the sandstone bodies in the two scenarios is clearly seen in the 3D model, viewed from the SW (Fig. 22).

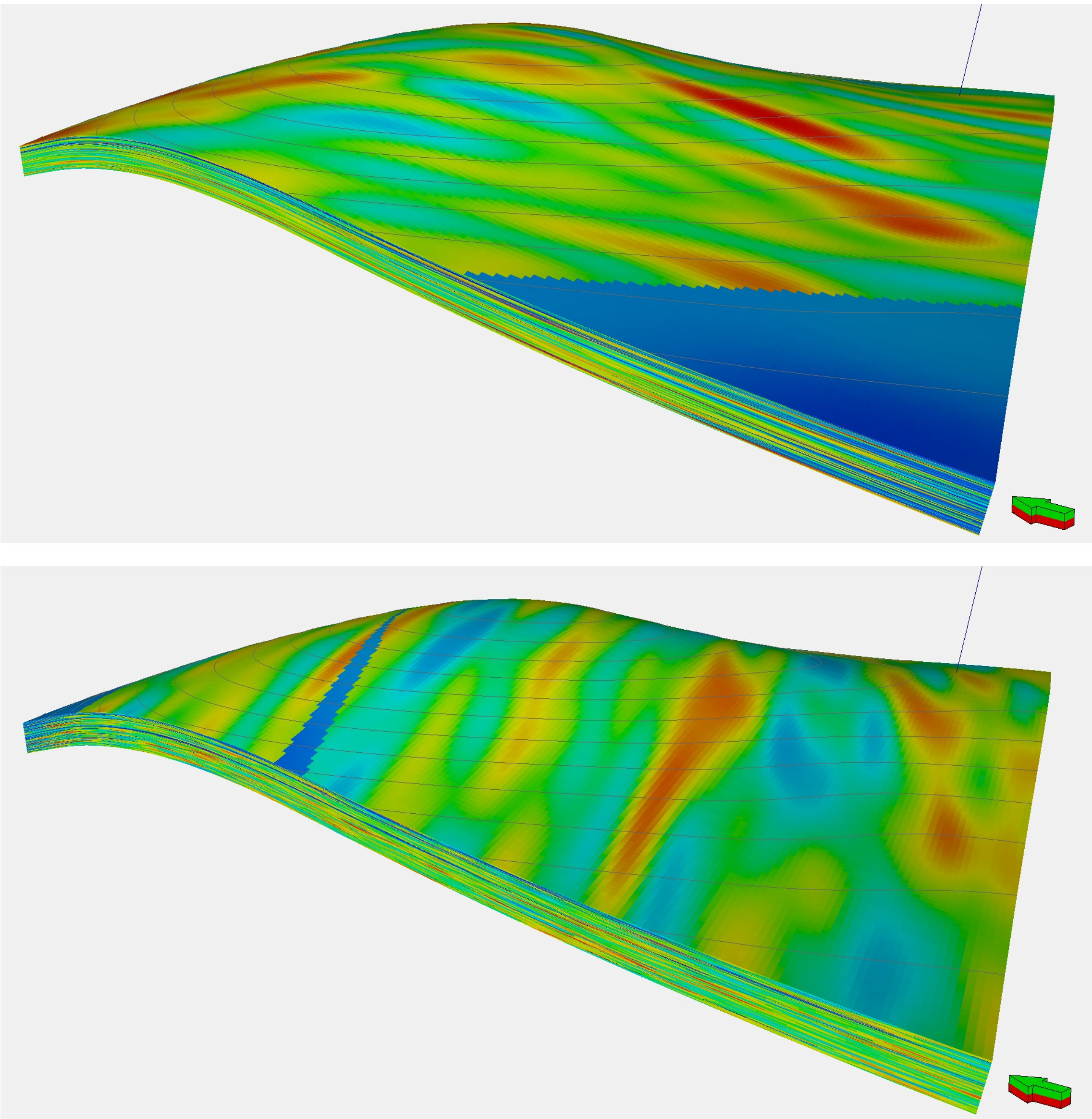

Figure 22. The 3D model of Gassum Fm porosity in the two scenarios for directions shown in model 2A and 2B, viewed from the SW. Vertical exaggeration is 5x. Contour line interval 50 m.

Finally, the facies model and the porosity models are exported and transferred to reservoir simulation.

Recommendations for supplementary investigations and research

This chapter relates to the present state of knowledge and the uncertainties involved in establishing a reservoir model for the Gassum Formation in the Havnsø area. This therefore indicates where new data and further investigations can improve the modelling. Some aspects are under investigation based on existing data, some definitely require new data for improvement, and some aspects might still be uncertain and therefore to be investigated with sensitivity studies exploring the probable ranges of the parameters under scrutiny.

Structural model

The main elements in a structural model of a storage site are: map of top surface of the reservoir, thickness map, and fault map.

The surface map is at present poorly described since the available seismic lines are sparse and not able to locate top point of the structure neither the spill point precisely.

The thickness of Gassum Fm is not known exactly due to the same restrictions as mentioned above in the data background.

Faults or fracture zones are not possible to distinguish in the present seismic data set. These features could be critical elements in evaluating the storage site for both subdivision of the reservoir layers into compartments which would complicate the filling of the structure, and for evaluating the faults as risk elements.

Therefore, a new data collection campaign obtaining quality seismic data is highly needed.

Facies model

The present facies model relies entirely on extrapolation of the preliminary interpretations at Stenlille some 30 km to the SE. Although the overall depositional system is supported by several wells also outside the Stenlille site, the exact pattern of important and influential elements in deposition such as estuaries or local sediment sources into the marine environment, incised valleys giving rise to erosion and down-cutting of transgressive surfaces, or the influence on sedimentation from the magnitude of tidal forces and regional sea-level fluctuations are all very uncertain.

For obtaining this information, a new seismic survey with high resolution data and optimized for processing aimed at unravelling the internal texture in the Gassum Fm would give an important input to the depositional pattern.

The drilling of an exploration well tied precisely to new seismic data and obtaining quality well logs and core material would further support a better definition of the local depositional system and thereby better modelling of the sediment body geometries.

Porosity model

The present porosity model is based exclusively on extrapolation of data from the Stenlille wells. However, the distance between Stenlille and Havnsø limits the confidence in the use of the Stenlille analogue despite the quality and amount of available well logs and core material from the Gassum Fm in the Stenlille wells. The interpretation of the Havnsø structure is thus hampered by the absence of data from the structure.

The core material is an extremely important element for the interpretation and calibration of the well logs and for the interpretation of the depositional processes that supports the facies patterns possible.

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