Research Article
2D Basin Modelling and Petroleum System Analysis of the Triassic Play in the Hammerfest Basin of the Norwegian Barents Sea

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Abstract: This study seeks to demonstrate the methodology used in 2D basin modelling, enhance the understanding of the Triassic play in the Hammerfest Basin and to show how basin modelling can be used to reduce exploration risk and improve exploration success using the Triassic play in the Hammerfest Basin in the Norwegian Barents Sea as a case study. 2D basin modelling has been done for the Triassic play in the Hammerfest Basin using Petromod software. The play consists of a source rock (Fruholmen formation) of Triassic age, a reservoir (Sto formation) of Middle to Lower Jurassic age and seals of Cretaceous and Upper Jurassic age. Three episodes of erosion (uplifts) in the Late Cretaceous, Paleogene and Paleogene-Neogene have occurred in the basin breaching the integrity of the seal and allowing the escape of hydrocarbons from the trap in some places. These episodes of erosion have increased exploration risks in the Hammerfest Basin and Barents Sea in general. Migration from the source rock into the trap is mainly upwards vertical migration. However, in areas where the hydrocarbons have escaped through the faults at the boundaries of the basin, migration in the layers above the trap is mainly lateral. The hydrocarbons generated are both gas and oil but are predominantly gas. The Upper Jurassic Hekkingen formation in the Barents Sea is a good source rock rich in organic matter with high values of hydrogen index and total organic matter but it doesn't seem to be matured in the Hammerfest Basin.

Keywords: Barents sea, basin modelling, hammerfest basin, petroleum system, triassic play

INTRODUCTION

A petroleum system is a geologic system that encompasses the hydrocarbon source rocks and all related oil and gas and which includes all of the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist (Magoon and Dow, 1994) (Fig. 1). A petroleum systems model is a digital data model of a petroleum system in which the interrelated processes and their results can be simulated in order to understand and predict them (Hantschel and Kauerauf, 2009). Basin modeling is dynamic modeling of geological processes in sedimentary basins over geological time spans (Hantschel and Kauerauf, 2009). The geological processes calculated and updated at each step include deposition, erosion, compaction, heat flow analysis, expulsion, phase dissolution, hydrocarbon generation, accumulation and migration. These processes are simulated in a dynamic petroleum systems model in the assessments of exploration risks, migration scenarios and drainage areas. The model seeks to answer questions such as whether hydrocarbons have been generated, where they have been generated, when they were generated, the properties of the hydrocarbons generated and the prospects the hydrocarbons have migrated into.

The Barents Sea is part of the Arctic Ocean situated between the Norwegian-Greenland Sea, Noraya-Zemlya, the Arctic Ocean Margin and the Norwegian-Soviet mainland (Fig. 2) (Johansen et al., 1992). By the end of 1989 some 22 and 45 exploration wells had been drilled in the Soviet and Norwegian parts of the Barents Sea respectively with 250,000 km of seismic acquired in Soviet waters and 423,000 in Norwegian waters (Johansen et al., 1992).

The Barents Sea region has an intracratonic setting and has been affected by several episodes of tectonism since the Caledonian Orogenic movements terminated in Early Devonian times (Gabrielsen et al., 1990). The Triassic to Early Jurassic is regarded as a tectonically relatively quiet period, however, the Stappen and Loppa Highs experienced tilting and the Early Triassic was characterized by subsidence in eastern areas and sediment influx from the east (Gabrielsen et al., 1990). Block faulting started again in the Mid Jurassic and increased during the period from Late Jurassic into Early Cretaceous, terminating with the formation of the now well known major basins and highs and finally
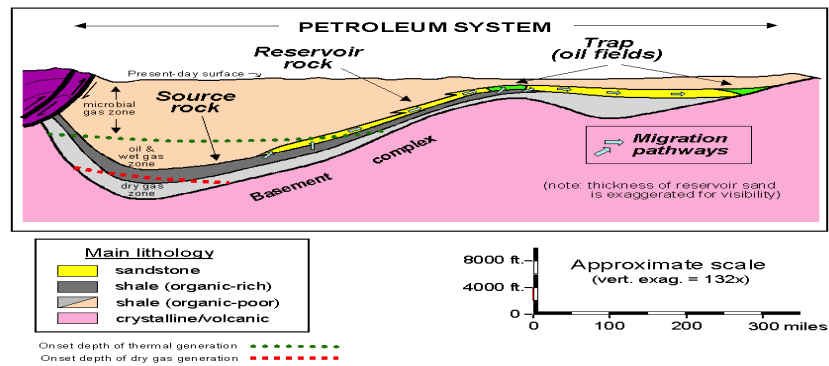
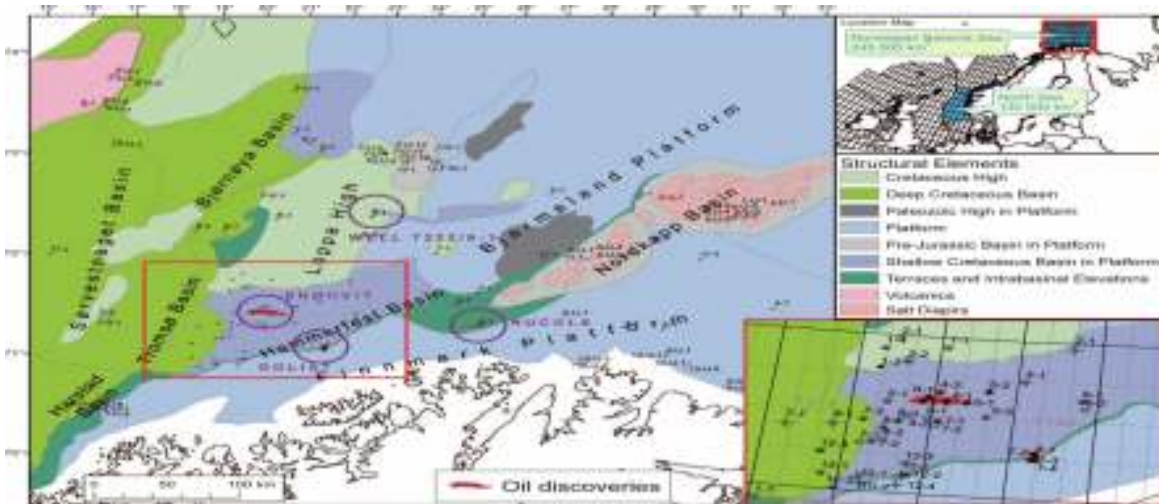Fig. 1: The main elements of a petroleum system (Magoon and Dow, 1994)

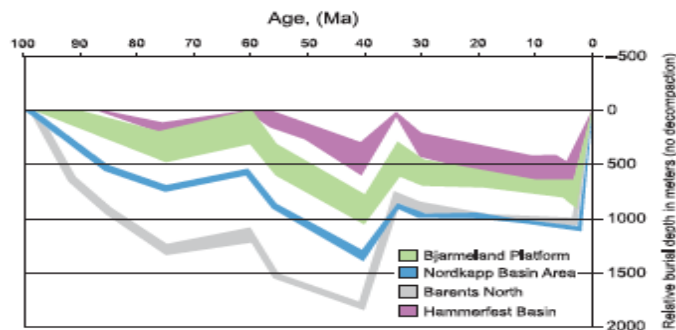Fig. 2: Location map of the Hammerfest basin in the Norwegian Barents Sea (Ohm *et al.*, 2008)

Fig. 3: Subsidence curves of the various parts of the Norwegian Barents Sea showing three episodes of uplift (Ohm *et al.*, 2008)

reaching maximum inversion and folding in the Eocene to Oligocene times (Gabrielsen *et al.*, 1990). Structurally, the Barents Sea continent shelf is dominated by ENE-WSW to NE-SW and NNE-SSW to NNW-SSE trends with local influence of WNW-ESE striking elements and in the southern part, a zone dominated by ENE-WSW trends is defined by the major fault complexes bordering the Hammerfest and Nordkapp Basins (Gabrielsen *et al.*, 1990).

The Norwegian portion of the Barents Sea has multiple petroleum systems representing an example of an overfilled petroleum system, however, several episodes of uplift and erosion from the Paleocene until the Pliocene-Pleistocene have caused the depletion of hydrocarbon accumulations in the region (Fig. 3) (Ohm *et al.*, 2008).

Gabrielsen *et al.* (1990) described the Hammerfest Basin as relatively shallow with an ENE-WSW striking
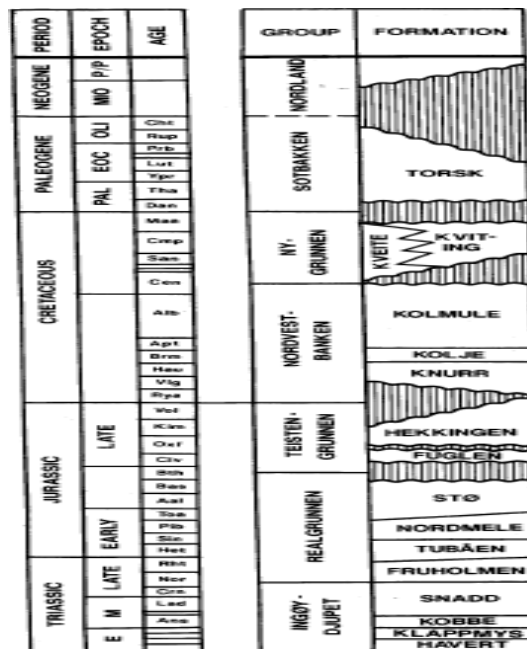
Fig. 4: Stratigraphic nomenclature of the Norwegian Barents Sea (Gabrielsen *et al*., 1990)

axis and is situated between 70º50'N, 20ºE, 71º15'N, 20ºE, 72º15'N, 23º15'E and 71º40'N, 24º10'E. The basin is separated from the Finnmark Platform to the south by the Troms-Finnmark Fault Complex, from the Loppa High to the north by the Asterias Fault Complex, limited towards the west by the Tromso Basin which is defined by the southern segment of the Ringvassoy-Loppa Fault Complex whereas its eastern border at the reference level has the nature of a flexure against the Bjarmeland Platform (Fig. 4) (Gabrielsen *et al*., 1990). The Hammerfest Basin has been interpreted as a failed rift in a triple junction (Talleraase, 1979) and as a remnant of an older rift system overprinted by a younger one (Hanisch, 1984a, b). Rønnevik *et al*. (1982) and Rønnevik and Jacobsen (1984) emphasized the influence of strike-slip faulting in the development of the fault complexes encompassing the basin. According to the Norwegian Petroleum Directorate (NPD), the petroleum system in the Hammerfest Basin consists of three petroleum plays namely:

- Upper Jurassic-Lower Cretaceous Play
- Lower-Middle Jurassic Play
- Triassic Play

The focus of this study is on the Triassic play. The Triassic sandstones belong to the Sassendalen Group consisting of the Havert, Klappmyss and Kobbe Formation and also the Snadd Formation which belongs to the Kapp Toscana Group that have been deposited in fluvial, deltaic, shallow marine, tidal and estuarine environments (Fig. 5) (NPD, 1996). The source rocks are mainly Upper Devonian- Lower Carboniferous
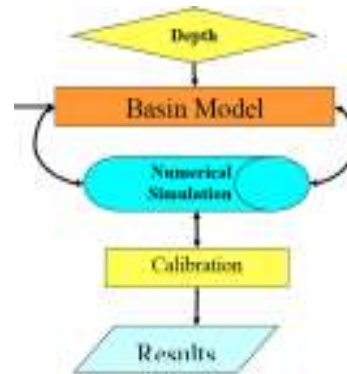

Fig. 5: Modelling work flow

shale, Lower Carboniferous coal and Upper Permian shale with the petroleum traps being dominantly stratigraphic and structural (rotated fault blocks and halokinetic) (NPD, 1996).

The lack of success in finding commercial hydrocarbon accumulations in the Norwegian Barents Sea and by extension the Hammerfest basin has been linked to the uplift in the basin by several researchers. These factors include low pressure in the reservoirs due to the uplift and erosion (Nyland *et al*., 1992), tilting as a result of differential uplift resulting in spillage from pre-uplift hydrocarbon accumulations (Dore and Jensen, 1996), failure of seals (Sales, 1993), cooling of the source rocks with subsequent cessation in hydrocarbon generation (Tissot and Espitalie, 1975) and lower reservoir quality than expected because of it having been buried deeper than present day depth (Bjorlykke, 1983; Berglund *et al*., 1986). The objective

of this study therefore is to demonstrate the methodology used in 2D basin modelling and to show how basin modelling can be used to enhance the understanding of a petroleum system, reduce exploration risk and improve exploration success using the Triassic play in the Hammerfest Basin in the Norwegian Barents Sea as a case study.

METHODOLOGY

The types of data used in building a model usually depend on the purpose of the model and the dimension.

The complexity and number of input parameters increase as you move from 1D to 3D models. Basin modelling workflows have been discussed by previous workers such as Hantschel and Kauerauf (2009), Waples (1994) and Tissot *et al.* (1987). The three major stages involved in this model building include the basin modelling stage, numerical simulation stage and calibration stage. The basin modelling stage is the foundation of the model and begins with the development of a conceptual model which has been subdivided into sequence of events (deposition, erosion and non deposition) of certain age and duration (Belaid

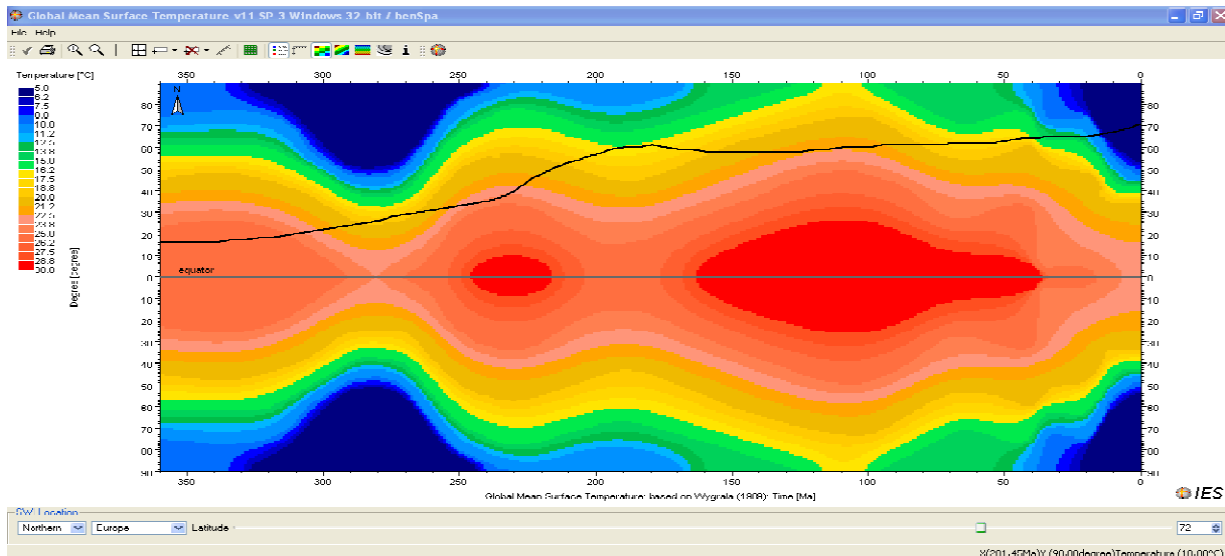Fig. 6: Facies definition table

Fig. 7: Sediment Water Interface Temperature (SWIT) definition

et al., 2010). The work flow involved is summarized in Fig. 5. 2D modelling integrates seismic, stratigraphic and geological data with multi-dimensional simulations of thermal, fluid-flow, petroleum generation and migration.

Data used in this modelling were obtained primarily from well data on the website of the Norwegian Petroleum Directorate and published data. The model was built using the Petrobuilder module in Petromod. The most important building block used in this 2D modelling is a cross section of the Hammerfest Basin which is imported into Petrobuilder and then digitized. In this work, a simple basic model is built first before proceeding to apply erosion to the model. The facies of the various formation and the petroleum system elements are defined in the facies definition table (Fig. 6). Twelve layers have been defined in the age assignment table as compared to 10 facies in the facies definition table because one or more layers can have the same facies. For example, the Paleogene and Paleogene-Neogene layers have been assigned the same facies.

The petroleum system elements in the basin such as source rock, reservoir and seal are also defined. The source rock is Fruholmen formation (TOC 9.9% and HI 195), the reservoir rock is Sto formation and the seals are Hekkingen and Kolmule formations. The reaction kinetics used is Burnham (1989) _TIII. One of the core aims of basin modelling is to build a model which can be simulated from the start of deposition to present day. Therefore, one of the most important aspects of building a model is the assigning of ages. This is done in the age assignment table in Petromod. Erosions (uplifts) are also defined in the age assignment table. To define erosion, data on the age of the erosion and the thickness eroded is needed. In the Hammerfest Basin, there have been three episodes of uplift and all these have been defined in the model. The uplifts occurred between the age 75-60 Ma in the Late Cretaceous (200

m), 40-35 Ma in the Paleogene (300 m) and 5.3-2.6 Ma in the Paleogene-Neogene (500 m). A total thickness of 1000 m has therefore been modelled.

Boundary conditions define the basic energetic conditions for temperature and burial history of the source rock and, consequently, for the maturation of organic matter through time (Petromod 3D tutorials 2009). Three main boundary conditions need to be defined in basin modelling namely Heat Flow (HF), Paleo Water Depth (PWD) and Sediment Water Interface Temperature (SWIT). The HF trend first needs to be created and then assigned to the model. Heat flow determines the maturity of the source rock. Heat flow values have been defined and assigned to the model from 0 ma (40 Mw/m^2) to 300 ma (70 Mw/m^2). Heat flow values in the Barents Sea usually vary between 50-75 Mw/m^2 (Eldhom *et al.*, 1999). The highest value of 75 has been assigned to periods of extensive rifting and faulting whereas the lowest heat flow values have been assigned to periods of uplift and erosion. The SWIT is defined using the automatic function in Petromod. The hemisphere is defined as northern and the latitude as 72 (Fig. 7). The hemisphere and latitude option are set based on the location of the Hammerfest Basin. The PWD in the Barents Sea varies between 300 to 500 m (Lambeck, 1995).

Calibration of the model was done using calibration parameters such as vitrinite reflectance (Ro), maximum temperature (Tmax) and Bottom Hole Temperature (BHT). There are several calibration models available to use in Petromod. In this case, the vitrinite model used is Sweeney and Burnham (1990) easy% Ro and the Tmax model used is Pepper and Corvi (1995) _TII (B). The model is simulated using the hybrid migration method in Petromod. The Hybrid migration method is a combination of both Darcy and Flow path algorithms and a simplified percolation calculation.
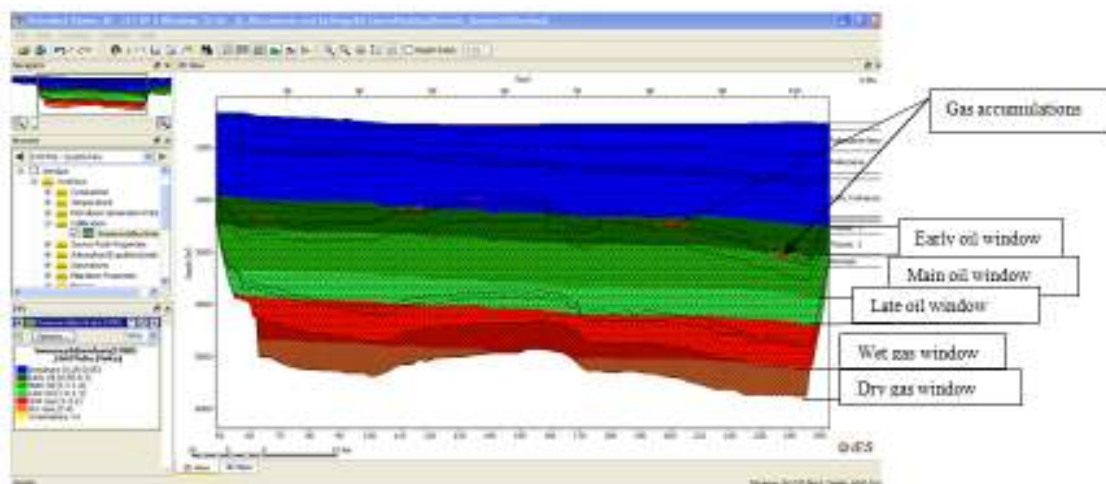

Fig. 8: Vitrinite reflectance overlay and hydrocarbon accumulations

RESULTS AND DISCUSSION

Source rock maturity and hydrocarbon windows:
The final simulated model of the Hammerfest basin as displayed in the 2D viewer module of Petromod and the resulting accumulations is shown in Fig. 8. The model is overlaid with the Sweeney and Burnham (1990) easy% Ro vitrinite reflectance model. The accumulations are mainly gas (red) with just minor amount of oil (green). Figure 8 shows the various hydrocarbon windows and this is summarized in Table 1. The main oil window is between 3.4-3.9 km whiles the main gas window is between 3.9-4.9 km.

Hydrocarbon migration: The migration pathways are mainly vertical from the source rock up into the

Table 1: Hydrocarbon generation windows

Hydrocarbon type	Depth (km)	Vitrinite Reflectance (VRo)
Early oil window	2-2.5	0.55-0.7
Main oil window	2.5-3.4	0.7-1.0
Late oil window	3.4-3.9	1.0-1.3
Wet gas window	3.9-4.9	1.3-2.0
Dry gas window	4.9-5.5	2.0-4.0

reservoir (Fig. 9). Some of the hydrocarbons have migrated along the faults bounding the model into the layers above the reservoir. The hydrocarbons that have breached the seal in these areas tend to migrate laterally as well when they get into the Early Cretaceous layer above the trap.

Burial history, erosion and uplift: Figure 11 to 25 show the deposition of each of the layers in the basin.
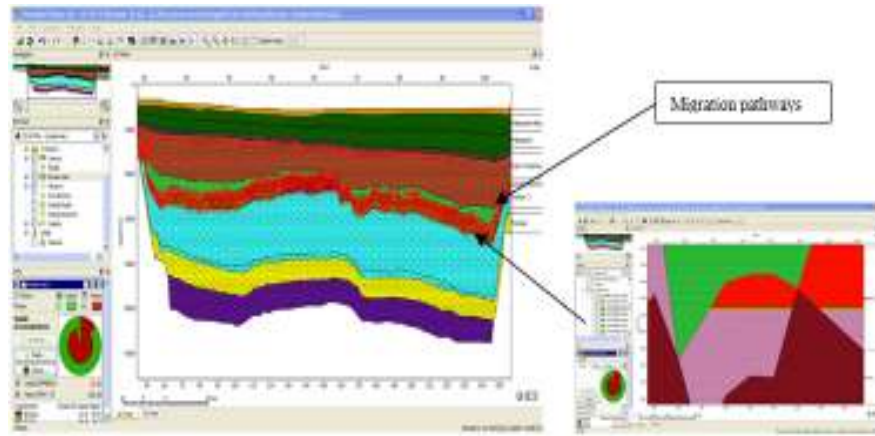

Fig. 9: Migration pathways in the Hammerfest Basin showing oil (green) and gas (red) accumulations
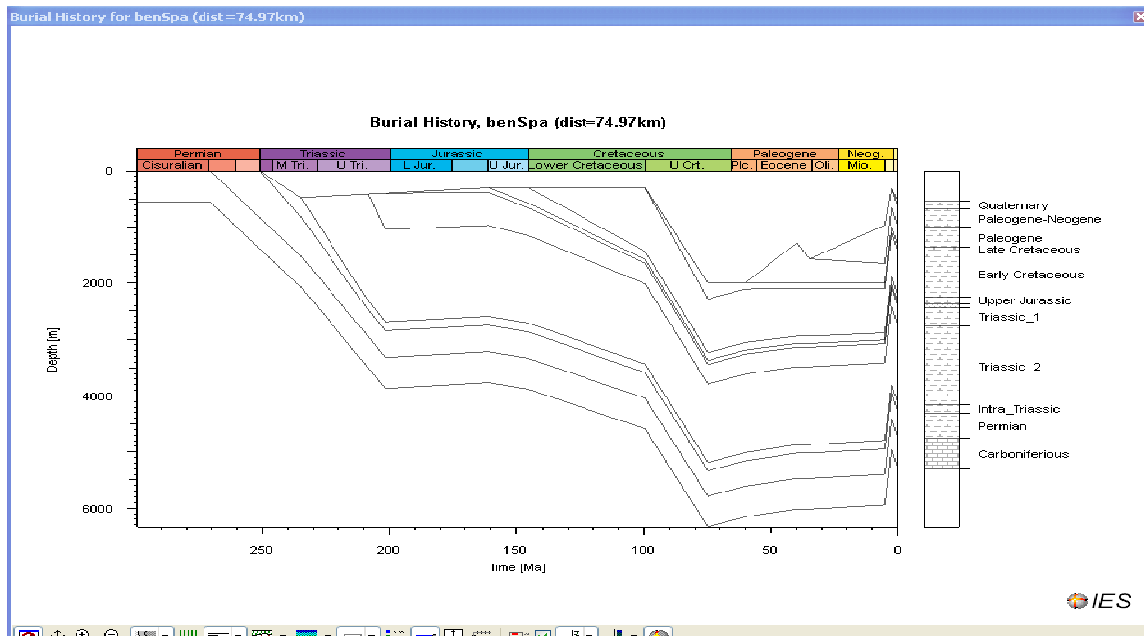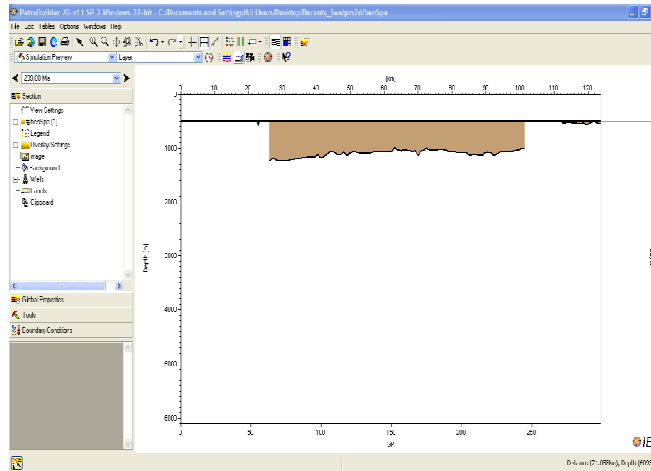

Fig. 10: Burial history graph

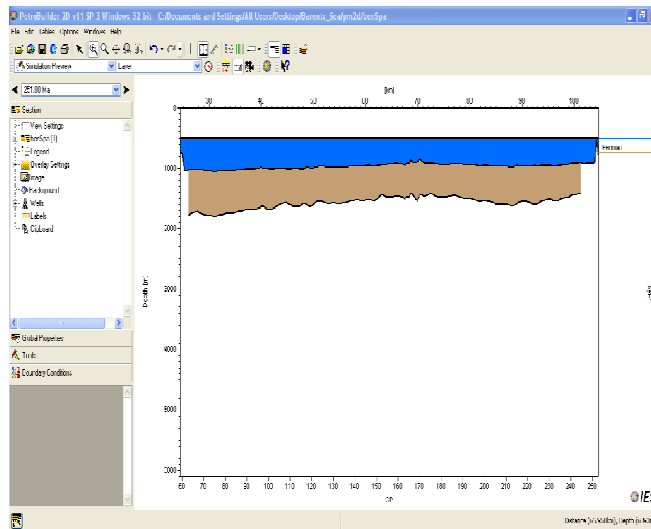Fig. 11: 359-299 Ma, deposition of the carboniferous layer

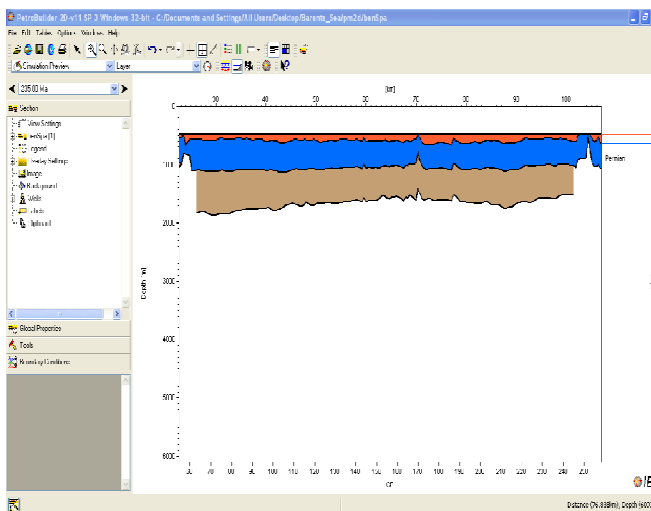Fig. 12: 299-251 Ma, deposition of the permian layer

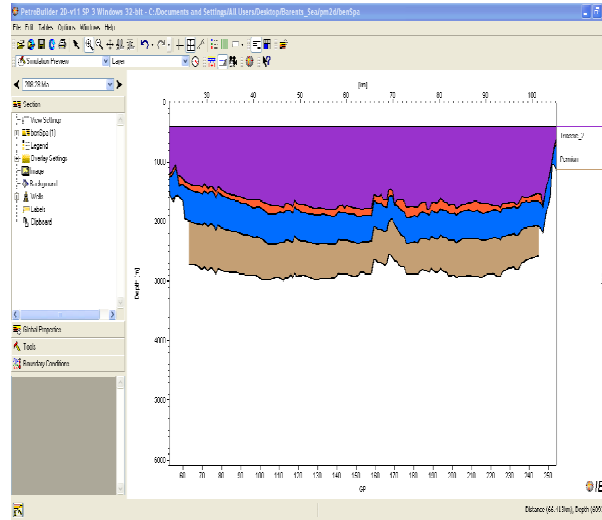Fig. 13: 251-235 Ma, deposition of the intra-triassic layer

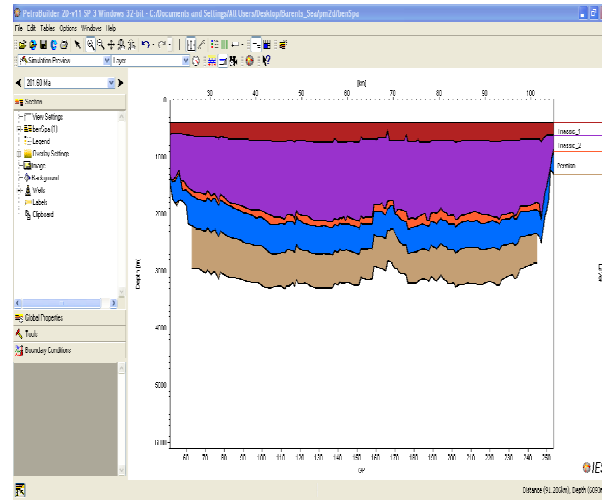Fig. 14: 235-208.28 Ma, deposition of the Triassic_2 layer

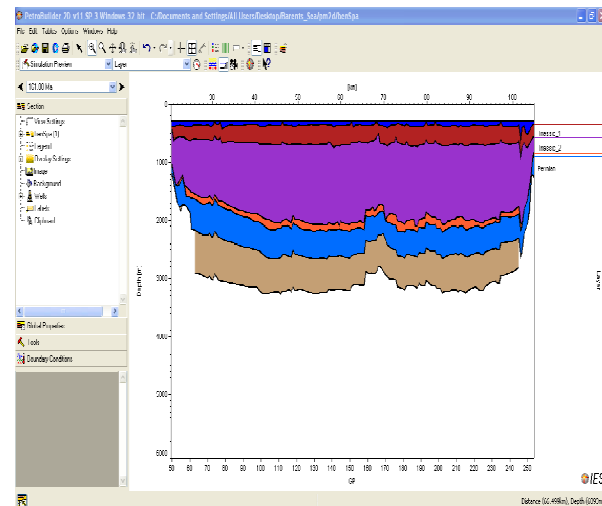Fig. 15: 208.28-201.6 Ma, deposition of the triassic_1 (source rock) layer

Fig. 16: 201.6-161 Ma, deposition of the middle-lower Jurassic (reservoir) layer
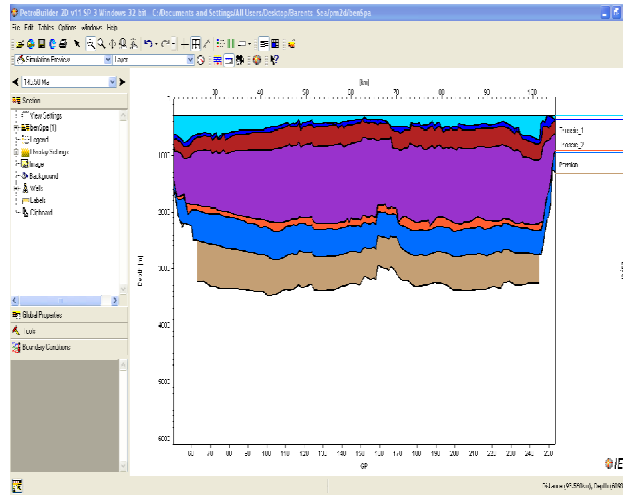
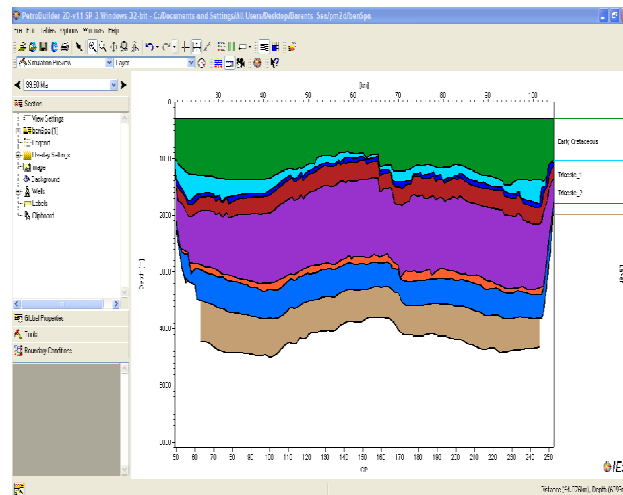Fig. 17: 161-145.5 Ma, deposition of the upper Jurassic (seal) layer

Fig. 18: 145.5-99.6 Ma, deposition of the early cretaceous (seal) layer
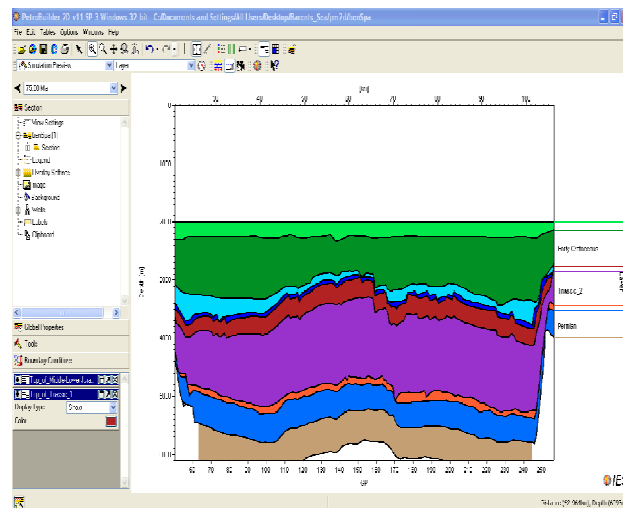
Fig. 19: 99.6-75 Ma, deposition of the late cretaceous layer

Fig. 20: 75-60 Ma, first erosion (uplift) in the late cretaceous resulting in the reduction in layer thickness of the late cretaceous layer compared to its thickness in 99.6-75 Ma above

Fig. 21: 60-40 Ma, deposition of the paleogene layer

Fig. 22: 40-35 Ma, second erosion (uplift) in the paleogene resulting in the reduction in layer thickness of the paleogene layer compared to its thickness in 60-40 Ma above
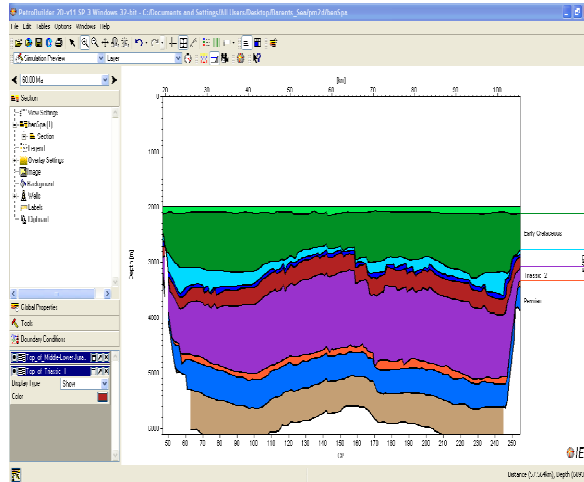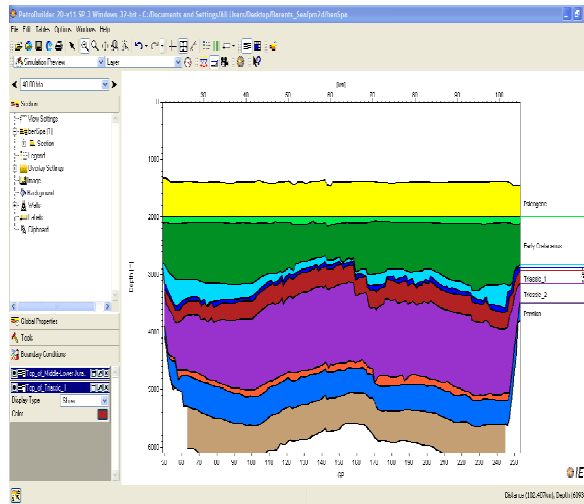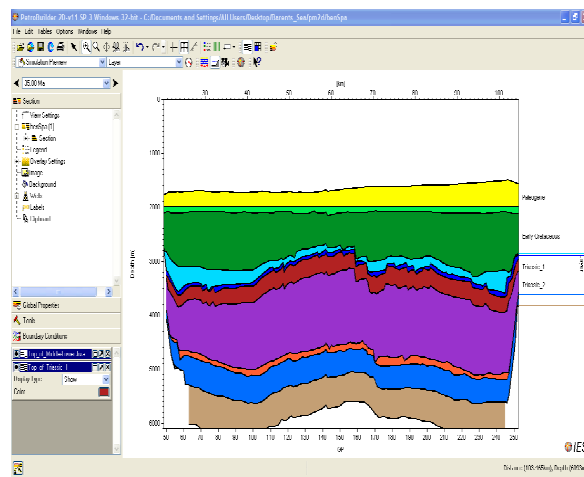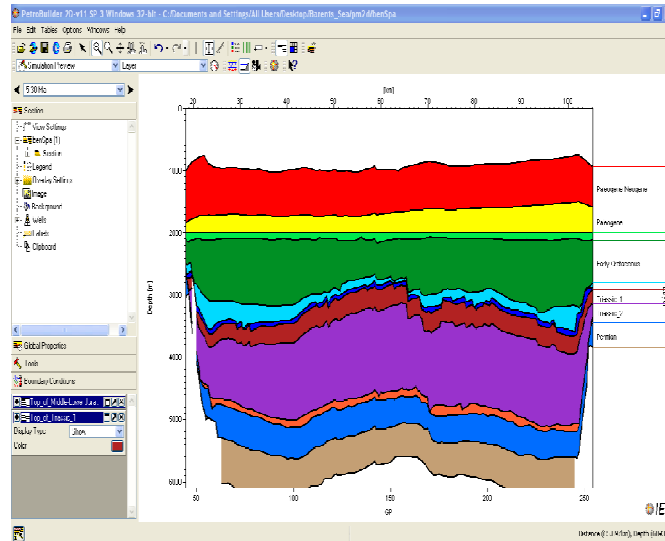
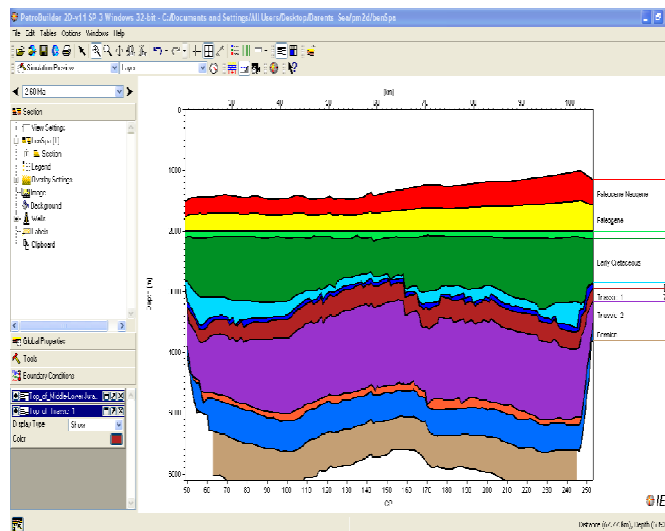Fig. 23: 35-5.3 Ma, deposition of the paleogene-neogene layer

Fig. 24: 5.3-2.6 Ma, third erosion (uplift) in the paleogene-neogene resulting in the reduction in layer thickness of the paleogene-neogene layer compared to its thickness in the 35-5.3 Ma above

The three episodes of erosion and uplift that have occurred in the basin occurred during the Late Cretaceous (5.3-2.6 Ma), Paleogene (40-35 Ma) and Paleoene-Neogene (75-60 Ma) respectively (Fig. 10). The erosional and uplift events are very important in the Hammerfest Basin especially in the areas where the uplift is maximum. In these areas, the uplift has resulted in a decrease in temperature halting the generation of hydrocarbons locally. These uplifts and erosional events have caused the redistribution of the remaining oil and gas over laterally large distances in the Barents Sea region thus charging traps, which otherwise would not have been reached (Ohm *et al*., 2008). Many oil accumulations in the region represent various mixtures of oils from several different stratigraphic source intervals suggesting that Triassic and Paleozoic oils may be trapped below the presently drilled targets, which are mostly Jurassic in the Hammerfest Basin and older to the N and E (Ohm *et al*., 2008).

The Upper Jurassic Hekkingen formation is known to be one of the rich source rocks in the Barents Sea. However, from the temperature and maturity graphs, it does not seem matured enough to generate commercial quantities of hydrocarbons.

Risking: Risk assessment is a very important part of hydrocarbon exploration. Petrorisk in Petromod provides risk assessments for the trap, reservoir and charge. The uncertainty related to trap is mainly related to uncertainties in the erosion thickness. Uncertainties
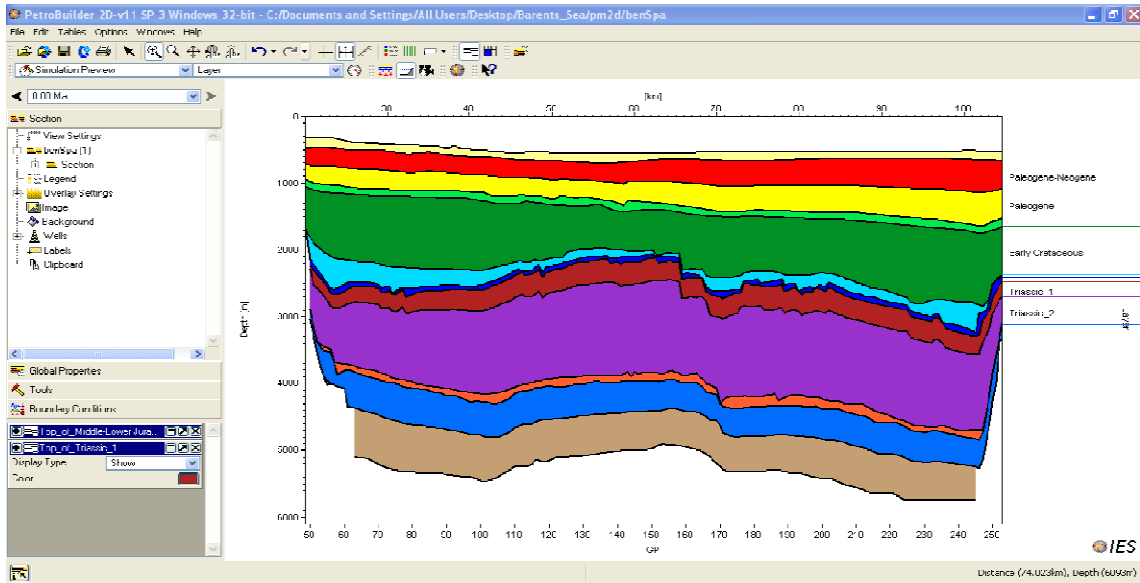
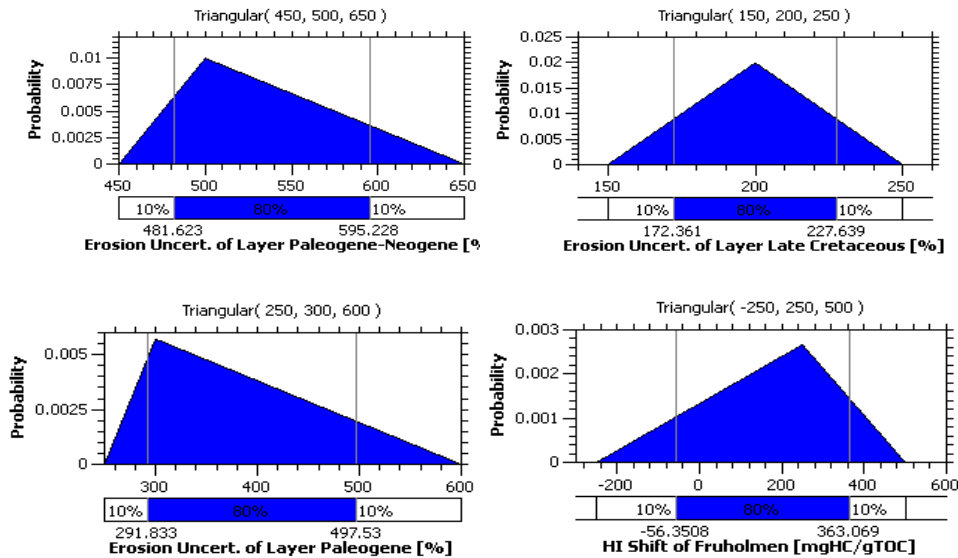Fig. 25: 2.6-0.00 Ma, deposition of the quartenary layer

Fig. 26: Uncertainties in erosion thickness of the trap and HI shift of the source rock (fruholmen formation)

relating to trap and charge have been defined in this modelling. There is 80% chance that the thickness of the Paleogene-Neogene erosion is between 481.6 and 595.2 m (Fig. 26). There is also a 10% chance that the erosion thickness may be below 481.6 m or 10% chance that the erosion thickness may be above 595.2 m (Fig. 26).

CONCLUSION

Migration from the Fruholmen source rock (Triassic 1) into the Sto formation (Middle to Lower Jurassic reservoir) is mainly upwards (vertical). However, hydrocarbons have breached the boundaries of the seal and migrated along the faults bounding the seal into the Early Cretaceous Kolmule formation where migration is mainly lateral.

The Upper Jurassic play with the Hekkingen formation as it source rock seems to hold very great potential in the Hammerfest Basin and the Barents Sea in general. The Hekkingen formation is rich in organic material and has high total organic content and hydrogen index. However, it doesn't seem to be matured enough to generate commercial quantities of hydrocarbons in the Hammerfest Basin.

Most of the hydrocarbons generated in the Hammerfest Basin are gas. Minor amounts of oil are generated. This observation is supported by the

predominantly gas field, Snohvit discovered in the Hammerfest Basin. However, there have been some oil discoveries in the Hammerfest Basin as well and this is supported by the Goliath and Nucula discoveries.

The uplifts and erosion in the Hammerfest Basin and Barents Sea in general have affected the integrity of the seals in the Basin causing leakage of hydrocarbons in many areas in the basin. This has increased the exploration risks immensely in the Barents Sea leading to the high number of dry wells. In the eroded and uplifted areas, hydrocarbon generation has ceased locally due to decrease in temperatures.

Finally, The Hammerfest Basin represents a petroleum rich province characterized by a number of plays. It is recommended that further basin modelling be carried out to better understand the petroleum system and characterize the different episodes of uplifts in the basin.

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