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Two-Dimensional Seismic Interpretation and Petroleum System Modelling in the Hammerfest Basin, SW Barents Sea

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Abstract

The Hammerfest Basin has undergone several structural and tectonic evolutions which affected its petroleum systems. Two-dimensional seismic interpretation and petroleum system modelling of the Hammerfest Basin was done in order to understand the petroleum system and effects of uplift and subsidence on hydrocarbon distribution, accumulations, maturity, migration and leakage. The central part of the Hammerfest Basin has been affected by Jurassic syn-rift faults forming a large graben structure in response to subsidence along the folded Asterias Fault Complex and Troms-Finnmark Fault Complex. The graben structure is characterized by gas chimney, bright spots and pockmarks. The modelling result shows that the Jurassic Hekkingen Formation is less mature (oil window) and that the Snadd and Kobbe Formations are mature to highly mature (gas window), respectively. The Stø and Tubåen reservoirs are enriched with oil and gas which migrated from the Snadd and Kobbe source rocks. The hydrocarbon accumulations show that the Stø Formation is the main reservoir in the Hammerfest Basin. Rapid burial during Permian and late Cretaceous was followed by uplift events. Three phases of erosion: the first two phases of erosion (75 to 60 Ma and 30 to 15 Ma) affected and eroded 200 m of Kveite Formation and 300 m of the Torsk Formation, respectively and the third phase of erosion (2.5 to 0.01 Ma) has eroded 100 m of Torsk Formation. The oil migration follows the deep seated faults along the Asterias Fault Complex, Troms-Finnmark Fault Complex and along the bounding faults of the graben structure at the center of the basin which leads to leakage. The migration of gas on the other hand, is vertically upward throughout the basin leaking out of the seal. The gas migration has been enhanced by the uplift and subsidence events which have been the main controlling factors of the hydrocarbon maturation and distribution within the Hammerfest Basin.

Keywords: Seismic interpretation; Petroleum system modelling; Erosion; Hammerfest basin; Source rock

Introduction

The Hammerfest Basin has undergone a long structural and tectonic evolution which has affected its petroleum systems [1]. Uplift and erosion in the Hammerfest Basin can have affected the integrity of the seals causing leakage of hydrocarbons [2-4]. This has increased the exploration risks leading to the high number of dry wells. In the eroded and uplifted areas, hydrocarbon generation has ceased locally due to a decrease in temperatures. The driving factors for the petroleum system of the Hammerfest Basin were uplift and erosion from the Paleocene til the Pleistocene which caused the depletion of hydrocarbon accumulations [5]. However, current investigations indicate that leakage is also a major exploration challenge in the basin [2,6-8]. Especially, petroleum system modelling and interpretation of the deeper horizons, including delineating the basement, have been another challenge. This paper will address the latter problem and provide information in the hydrocarbon potential of the study area through seismic interpretation and basin modelling. Basin modelling is a dynamic modelling of geologic processes include deposition, erosion, compaction, heat flow analysis, expulsion, phase dissolution, and hydrocarbon generation, accumulations, maturation and migration to know the sources, timing and prospectively of hydrocarbon. So, this work significantly help to (1) quantify the amount and timing of oil and gas generation in the basin, (2) estimate the hydrocarbon accumulation in the reservoirs, (3) reconstruct the possible hydrocarbon migration pathways, (4) evaluate the possible leakage from the source rocks and reservoirs and (5) elucidate the effect of geologic events such as glaciation, uplift and subsidence on petroleum systems in the basin.

The SW Barents Sea margin, along the Senja Fracture Zone, developed during the Eocene opening of the Norwegian–Greenland Sea, first by continent–continent shear followed by continent–ocean shear, and has been passive since earliest Oligocene time. After breakup, the passive margin evolved in response to subsidence and sediment loading during the widening and deepening of the Norwegian-Greenland Sea. Sedimentation was modest until the Late Pliocene when the Northern Hemisphere Glaciation led to rapid progradation and greatly increased sedimentation rates forming huge, regional depocentres near the shelf edge offshore Mid–Norway and in front of bathymetric troughs in the northern North Sea and western Barents Sea [9]. Tectonic, paleoceanographic and paleoclimatic events that had a crucial influence on the hydrocarbon accumulation and distribution in the entire Barents Sea during Cenozoic and some of the major related consequences (1) cessation of petroleum generation, expulsion and migration from the source rocks, (2) phase changes, including the expansion of gas in reservoir, which resulted in the spilling of earlier trapped oil, (3) reactivation of faults and breaching of seals associated to the reduction of overburden and pressure fluctuations, and (4) leakage of hydrocarbons from the reservoir to the surface, with the possible formation of gas hydrates and pockmarks [4,8,10-13].

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This work is therefore done to assess the petroleum system in the Hammerfest Basin through integrated approach of seismic interpretation and basin modelling. Fault and horizon interpretation, seismic-to-well tie, isochrone maps, velocity modelling and depth conversion were done to achieve this objective. The study area situated between latitude 70°50'-72°15'N and longitude 20-24°10'E and is bounded by the Finnmark Platform in the south and by the Loppa High and the Bjarmeland Platform in the north (Figure 1).

The evolution of the Hammerfest Basin

The Hammerfest Basin is a 150 km-long and 70 km-wide composite, asymmetric, elongated sedimentary basin, striking ENE/WSW. The basin is fault controlled and was probably established in the Late Carboniferous [14], although main subsidence occurred in the Triassic and the early Cretaceous. Basinal development largely culminated in the mid-Cretaceous, but highly condensed Upper Cretaceous and thin Lower Tertiary shales are also preserved in the basin, in spite of extensive late Tertiary uplift. There is no evidence of extensive late Palaeozoic evaporite deposition or of diapirism in the basin, in contrast to the Tromsø Basin to the west and the Nordkapp Basin to the east. The internal structure of the basin is characterized by a central dome located along the basin axis and by a complex pattern of dominantly westerly and west-northwesterly trending faults; all of these features predominantly reflect late Jurassic tectonism [15].

Seismic data indicate the presence of a thick Permian sedimentary sequence in the eastern part of the Hammerfest Basin area. Possibly this area was part of the Nordkapp Basin in Paleozoic times, a basin developed synchronous to the Devonian to Carboniferous basins on Bjørnøya and Spitsbergen [16]. The tilting of the basin in late Carboniferous to early Permian times was caused by tensional strike slip movement with reactivation of underlying sediment fault trends. The depositional conditions during Permian were dominantly marine with general basin subsidence where the depocenters are in the north-eastern and in the south-western parts of the present day Hammerfest Basin [1].

During the Triassic and early Jurassic the Hammerfest Basin was part of a regional basin. Its development as a separate depositional entity with flexuring and faulting of the northern flank and reactivation of rift was started during the Kimmeridgian rift phase and the northeastern Barents Sea from the western margin decoupled at this time [17]. After the main pulse of faulting, rapid subsidence followed by basin fill onlapping sequences on the flank of the basin was deposited [18,19]. The Middle and Upper Triassic sequences show an upward coarsening as result of the cyclic changes from open marine to the continental environments. The intercalation of shaley continental and sandy shallow marine sediments during late Triassic to mid-Jurassic sequences was controlled by complex inter-play of tectonic subsidence, eustatic sea-level changes and local sediment input [1]. The Hammerfest Basin is bordered to the west by a marked faulted hinge zone (RLFC). There is a marked thickening of Upper Jurassic-Lower Cretaceous across the hinge zone [18].

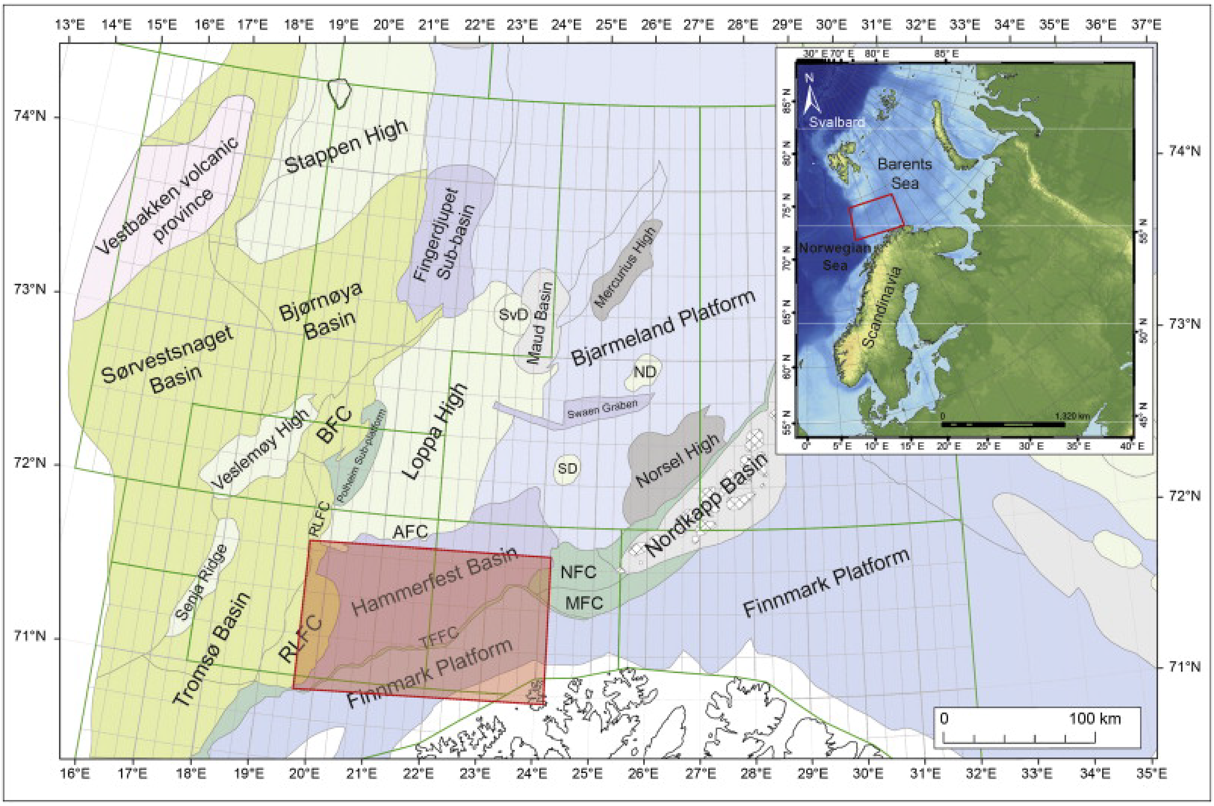

Figure 1: The red square shows the location of the Hammerfest Basin in the SW Barents Sea (AFC: Asterias Fault Complex; BFC: Bjørnøyrenna Fault Complex; MFC: Måsøy Fault Complex; ND: Nordvarg Dome; NFC: Nyslepp Fault Complex; RLFC: Ringvassøy–Loppa Fault Complex; SD: Samson Dome; SvD: Svalis Dome; SLHFC: Southern Loppa High Fault Complex; TFFC: Troms-Finnmark Fault Complex [12]. The inset shows the map of Northern Europe, with the approximate position of the study area.

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Tertiary sedimentation in the Hammerfest Basin was started during the mid-Paleocene. Concurrent with the initiation of a marine environment, due to a transgression of the central parts of the basin, erosion of the Loppa High and Finnmark Platform was prevailed. In mid-late Paleocene time these were gradually transgressed, contemporaneously with a bathyal environment in the central part of the basin. A south-southwesterly progradation from the platform areas north-northeast of the Hammerfest Basin was initiated during the late Paleocene [1]. This, possibly combined with high biogenic activity, led to high accumulation rates in the basin areas. As a response to compressional uplift of the southwestern part of the Loppa High during the late Paleocene/early Eocene, south-southwesterly progradation was initiated proximal to the Loppa High. In the west-central part of the basin, subsidence led to a more westerly oriented progradation. Coeval sedimentation in the southern part of the Hammerfest Basin was dominated by low-energy deposition in a non-prograding environment. The sediment response is speculated as mirroring the latest rifting phase and the earliest phase of seafloor spreading (56 Ma) of the Norwegian-Greenland Sea, which gave rise to transpression along the western margin, and along the western part of the Hammerfest Basin, transtension (i.e., the Ringvassoy-Loppa Fault Complex). The Oligocene and Miocene were dominated by subsidence of the western Barents Sea margin, and the basins on the shelf including the Hammerfest Basin were alternately accumulating sediments and undergoing erosion [20]. The lithostratigraphy and summarized description of the Hammerfest Basin is presented on Figure 2 and Table 1.

Materials and Methods

Two-dimensional (2D) seismic data and eight wells were used in this study. In the first phase, Seismic interpretation of five dip lines were selected and seismic-to-well tie was done using Petrel software, where the seismic has best fit with synthetic seismogram. The depths also have a good agreement with known depths from the wells. The synthetic seismogram has been created in Petrel synthetic generation tool where all of the three wells show a good match with the seismic data. Additionally, these wells were correlated to one another. Faults were marked based on breaks of discontinuity of reflectors with visible displacement. The prominent strong and continuous train of wavelets running across the seismic sections was marked as horizon. On this basis, fourteen horizons were mapped. From these horizons one representative dip-line (BSSO1-104) was selected and depth converted after velocity modelling using 2 km/s for the basin (Figure 3). In the second phase, the depth-converted 2D seismic line was loaded into PetroMod software and faults and horizons were digitized. Then, layer splitting has been done to insert multi erosion events and to split the Jurassic and Triassic sequences into formations. The facies and

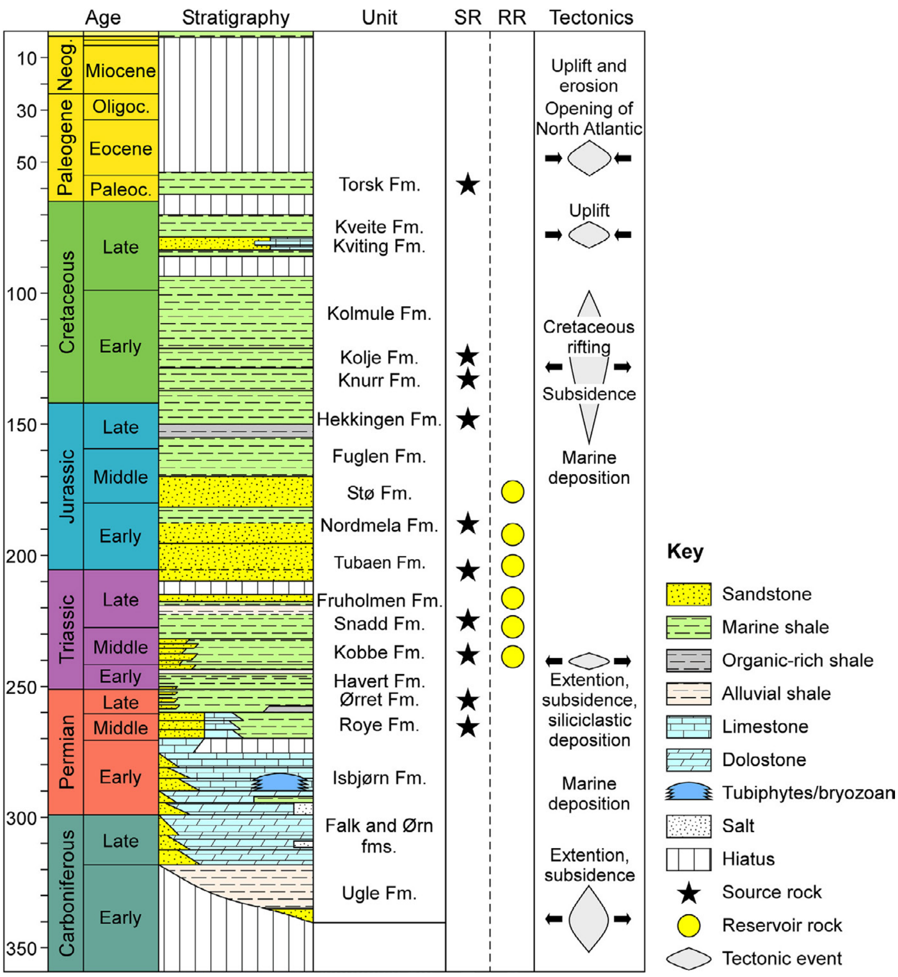

Figure 2: Lithostratigraphic chart of the Hammerfest Basin where potential source rocks (SR) and reservoirs (R) as well as the general overview of the geologic and tectonic history are composed from [4,5,21].

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erosion definition was done after age assignment and facies mapping as modified by Rodrigues Duran et al. [12] (Table 2).

The paleowater depth ranges from 300 m to 500 m [23]. The water depth from different wells was used in this model and is below 400 m. The upper boundary condition of heat transfer in sedimentary basins is given by the temperatures either at the sub-aerial surface or at the sediment water interface, and is affected by the water depth, the paleogeographic position, and oceanic currents [24]. The Sediment Water Interface Temperature (SWIT) values in this model were assigned based on time latitude diagram which ranges from 5-25°C [24]. The interglacial and the present-day SWITs are 3 and 6°C, respectively [25,26]. The heat flow was automatically found from PetroMod. It shows increases from 41 mW/m^2 (2.83 Ma) to 55 mW/m^2 (130 Ma) and then decreases again to 47 mW/m^2 (196 Ma). Then, hybrid (darcy+flow path) migration method was used for simulation. The optimization of the model (relative difference with the reality) was 0.03. Hence, it is less than 1% and the model was built successfully.

Results and Discussion

Seismic interpretation

Fourteen horizons were interpreted and named using the nomenclature of [14] and [27] (Figure 4). These include Lower Carboniferous (LC), Near Base of Permian (BP), Near Top of Permian (P1), Intra Lower Triassic (ILTR), Base Middle Triassic (BMTR), Intra-upper Triassic (IUTR), Base-upper Jurassic (BUJ), Intra Lower Cretaceous (?Hauterivian) (ILK1), Intra Lower Cretaceous (?Barremian) (ILK2), Intra Lower Cretaceous (ILK3), Base Tertiary (BT), Base Quaternary (BQ) and the Seabed (Figure 5). The bright reflectors shown locally in some parts are restricted laterally and different from the other strong reflectors. From IUTR to ILK1 the packages are thickening towards the discontinuities (AFC and TFFC) and thinning to the center of the basin in general. Some strong reflectors at the center of the basin between ILK1 and IUTR cross–cut the dip lines and are low amplitude and discontinuous on the strike lines.

The reflectors at the middle of the seismic section have different

Name	Lithology	Depositional environment	Age
Nordland Gp	Cst and clay rich sandstone	Bathyal to glacial marine	L.Pliocene to Holocene
Torsk Fm	Cst, (Sst, Lst)	Open to deep marine shelf	L.Paleocene to Oligocene
Kveite Fm	shales and Cst, (Lst, Slt)	Deep open shelf	Cenomanian to Maastrichtian
Kviting Fm	calcareous Sst, (Ms, Cst, Lst)	Deep to shallow shelf	Campanian
Kolmule Fm	Cst and shale, (Slt, Lst, Dlt)	Open marine environments	Aptian to mid-Cenomanian
Kolje Fm	shale and claystone, Lst, Dlt	Distal open marine	E. Barremian to E.Aptian
Knurr Fm	Cst, (Lst, Dlt)	Distal marine	Ryazanian to E.Barremian
Hekkingen Fm	shale and Cst, (Lst, Dlt, Slt, Sst)	Deep marine	E.Kimmeridgian to Ryazanian
Fuglen Fm	Mst, (Lst)	Highstand marine	L. Callovian to Oxfordian
Stø Fm	Sst, (shale, Slt)	Prograding coastal regimes	Pliensbachian to Bajocian
Nordmela Fm	Sst, (shale, Cst, coals)	Tidal flat to flood plain	Sinemurian to L.Pliensbachian
Tubåen Fm	Sst, (shale, coals)	Marginal marine	L.Rhaetian to E.Hettangian
Fruholmen Fm	Mst, (Lst, shale)	Highstand marine	L. Callovian to Oxfordian
Snadd Fm	Shale, (Slt, Sst)	Distal marine	Ladinian to E. Norian
Kobbe Fm	shale, (Slt, Sst)	base clastic marginal marine	Anisian
Havert Fm	shale (Sst, Slt)	Marginal marine to open marine	Griesbachian to Dienerian
Ørret Fm	Sst, Slt, shale	Deltaic and lower coastal plain	Kungurian to Tatarian

Table 1: Summary of lithostratigraphy of the Hammerfest Basin [22]. The lithologies in brackets are interbedded lithology. Gp: Group, Fm: Formation, Sst: sandstone, Cst: Claystone, Slt: Siltstone, Ms: mudstone, Lst: Limestone and Dlt: dolomite, E: early and L: late.

Name	TOC percentage (%)	HI (mgHC/gTOC)	PSE	SE Lithology
Nordland Gp (0.01-0 Ma)			OR	Siltstone (organic lean)
Torsk Fm (65.5-30 Ma)			OR	Shale (organic lean, typical)
Kveite-Kviting Fms (96.6-65.5 Ma)			OR	Siltstone (Organic lean)
Kolmule Fm (120-96.6 Ma)			OR	Shale (organic lean ,silt)
Kolje Fm (130-120 Ma)			OR	Shale (typical)
Knurr Fm (140.2-130 Ma)			OR	Shale (typical)
Hekkingen Fm (155.6-140.2 Ma)	10	300	SR	Shale (organic rich, 8% TOC)
Fuglen Fm (167.7-155.6 Ma)			SeR	Shale (organic lean, siliceous, typical)
Stø Fm (184-167.7 Ma)			RR	Sandstone (typical)
Nordmela Fm (196.5-184 Ma)			OR	Siltstone(Organic lean)
Tubåen Fm (200-196.5 Ma)			RR	Sandstone (clay poor)
Fruholmen Fm (210-200 Ma)			OR	Siltstone(Organic rich, 2-3% TOC)
Snadd Fm (237-210 Ma)	2	150	SR	Siltstone(Organic rich, 2-3% TOC)
Kobbe Fm (245-237 Ma)	3	200	SR	Siltstone(Organic rich, 2-3% TOC)
Klappmyss-Havert Fms (260-245 Ma)			UR	Shale (Organic lean, silty)
Ørret Fm (265-260 Ma)			UR	Shale (Organic lean, silty)
ILTR Fms			UR	Sandstone (typical)

Table 2: Facies and age definitions modified from [12]. Gp=Group, Fm=Formation, Fms=Formations, PSE=Petroleum system elements, OR=Overburden rock, UR=Underburden rock, SR=Source rock, SeR=Seal rock, RR=Reservoir rock, TOC=Total organic carbon, HI=Hydrogen index.

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quality and architecture; some of them are high amplitude and continuous while the others are low amplitude and highly discontinuous. The discontinuous reflectors are more dominant along the Asterias Fault Complex (AFC), Troms-Finnmark Fault Complex (TFFC) and graben structure at the center of the basin. The reflectors along the active fault zones of the Asterias Fault Complex and the Troms–Finnmark Fault Complex are highly curved up following the master fault planes. The tectono-sedimentary evolution of the normal fault array can cause the sediments to bend along the fault complexes followed by onlapping sediments. Syn rift faults cutting IUTR, BUJ and ILK1, were recognized by thickening towards the faults. The discontinuities on the reflectors are faults which have reflection shadow and vertical displacements. The fault plane on the strike and dip lines has different nature of reflectance. All are normal faults dipping to NNW and SSE, dominantly extending from BMTR to BT.

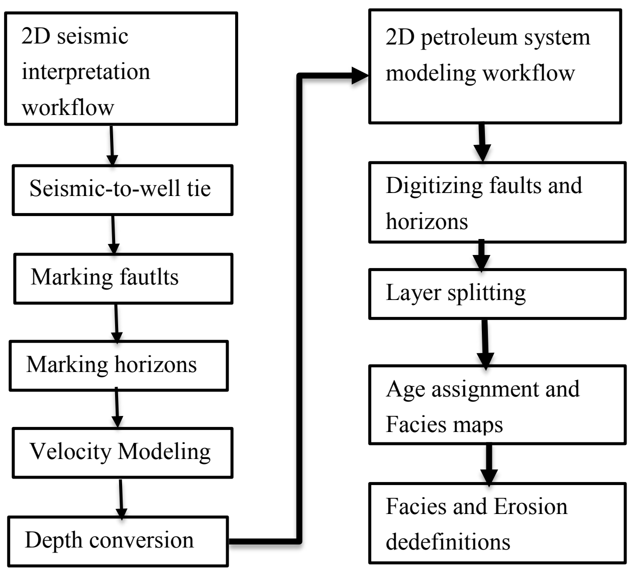

Figure 3: Workflow for 2D seismic interpretation and petroleum system modelling.

The Troms-Finnmark Fault Complex changes its dip angle at depth and becomes gentle and steeper again (Figures 4 and 5). The deeper part of this fault was identified based on the structural relationship of faults on the dip and strike lines. It is dipping to the north on the dip–lines. The nature of the fault plane at this portion and further depths is not the same to its upper part. This part of the fault plane shows strong reflectors showing high rheological differences in acoustic impedance. It may encounter the basement at this depth as gravity studies indicate the basement is approximately at 9-10 km depth [29]. The subsidence along the AFC and TFFC form synclines on both sides of the master faults caused an extension at the middle of the basin and subsequent subsidence leads to the formation of the graben structure.

Three possible phases of faulting have been identified based on repeated thickening of strata into the hanging wall of the basin near the faults. The first phase of rifting is the formation of the master faults e.g. Asterias Fault Complex and the Troms-Finnmark Fault Complex. It created accommodation space for the syn-rift sediments of Jurassic age. The second phase of rifting provides the Jurassic faults that extend to the intra-upper Triassic (IUTR) and Base of Middle Triassic (BMTR) as it can be evidenced from the folded strata in the AFC. The third phase of rifting can be the reactivation of the Jurassic faults which forms the graben structure at the middle of the Hammerfest basin. This continues up to Cretaceous and Tertiary formations. In this scenario, the formations above the Intra-lower Cretaceous (ILK1) are post-rift. The post rift formations are following the trend of syn-rift formations architecture at the base and become horizontal at the top. The deposition of the post rift significantly separated by erosional surface, at the Base Quaternary (BQ), since some of the Base Triassic to Intra-upper Triassic sediments are removed in the Finnmark Platform. The pre-rift formations are the Triassic and older formations. They have relatively uniform thickness throughout the basin. However, subsidence, uplift and fault-background collapse during the graben formation have affected the pre-rift sediments thickness along the flanks of the basin.

Stages of rifting from the reflectors architecture was used to identify the tectonic system tracts (Figure 6). S1 is the pre-rift stage to the Jurassic rifting phase and post rift to the Permian subsidence and rifting. The reflectors are parallel and uniform in thickness. The chaotic reflectors towards the master fault of Asterias Fault Complex

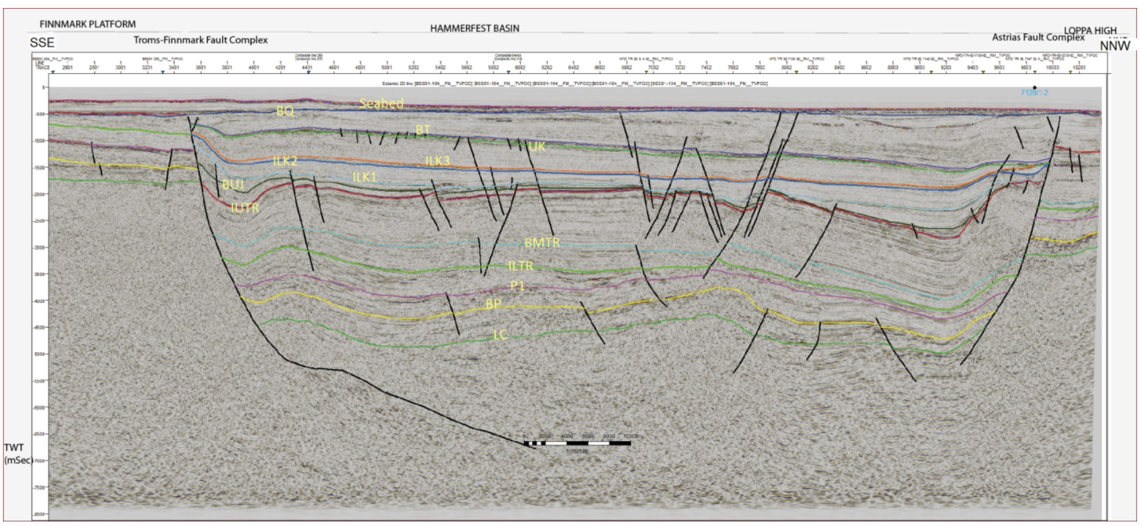

Figure 4: Faults and horizons interpretation of dip–line BSS01-104. 14 horizons and faults including the AFC and TFFC were interpreted.

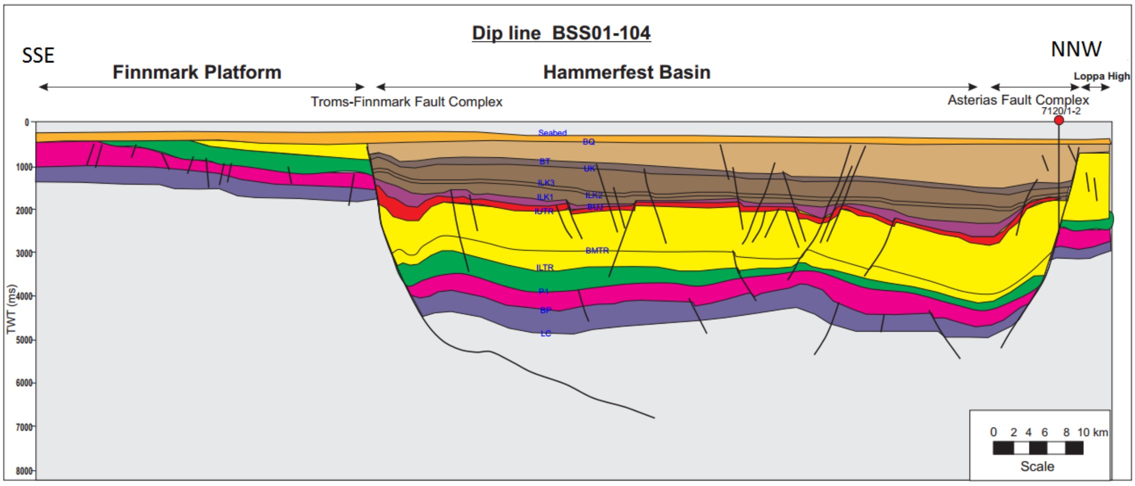

Figure 6: Stratigraphy of the Hammerfest Basin [28]. The colour code of the stratigraphy of the line from bottom to top is Carboniferous Formations (purple), Permian Formations (green),Triassic Formations (yellow), Jurassic Formations (red and pink), Cretaceous Formations (dark brown), Tertiary to Quaternary Formations (Light brown) and Quaternary and recent sediments (dark green).

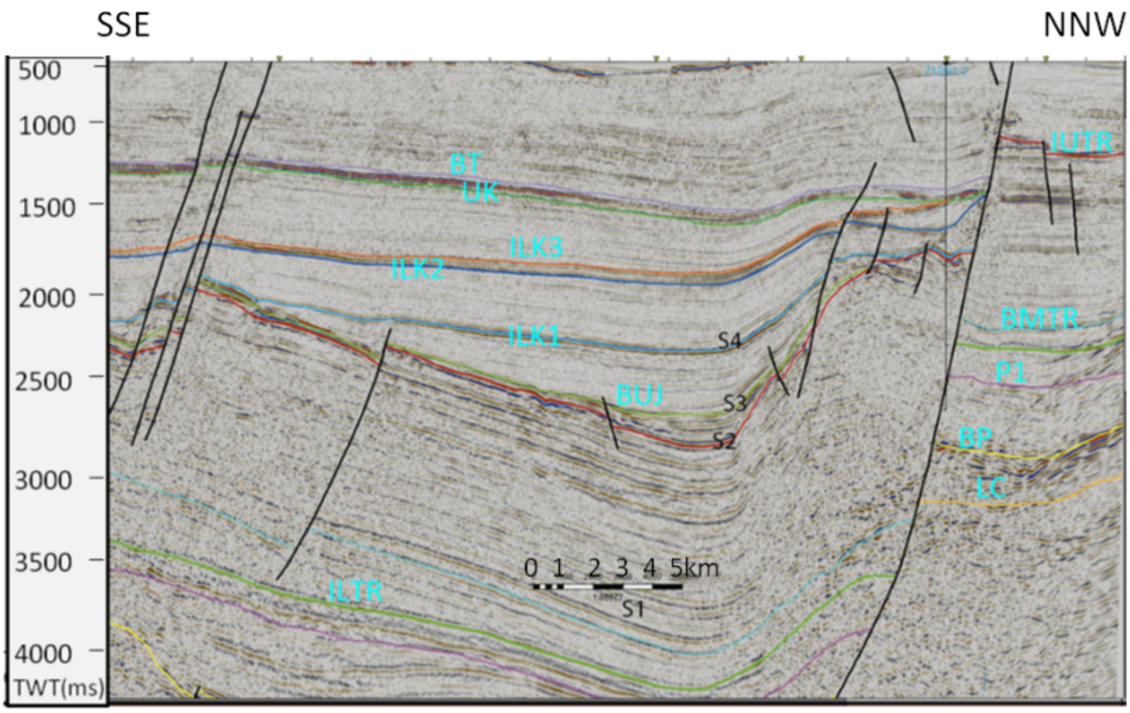

Figure 6: Stages of rifting and sedimentation based on the thickness variation and the architecture of the reflectors. S1: is the pre-rift stage, S2: the rift initiation stage, S3: is the rift climax and S4: post–rift stages are marking the tectonic and sedimentation evolution and their associated systems tracts.

can be coarse grained rock falls and talus. The rift initiation stage (S2) have wedge shape geometry where it is thicker towards the faults and thinner to its hanging wall by on lapping reflectors to the BUJ reflector. The accommodation space created by the rifting outpacing with subsidence has been filled with the Jurassic syn-rift sediments. After the rift climax stage (S4) the sedimentary layers start up- dipping towards the footwall shows the sediment supply is higher, the accommodation space formation by the rifting ceases. The post rift (S4) stage starts during Intra Late Cretaceous (ILK1). The tilting of the hanging wall and differential subsidence across the fault plane ceases and the rate of regional subsidence will decrease, although subsidence will continue due to the lithospheric thermal cooling effects.

Pockmarks are also visible along the seabed creating local depressions which are recognized in the seismic section [8,28] (Figure 7). They are dominantly seen above the fault graben structure. The graben is also characterized by the gas chimney and less clear reflectors from ILK1 to BQ. This indicates that pockmarks have a link with the gas

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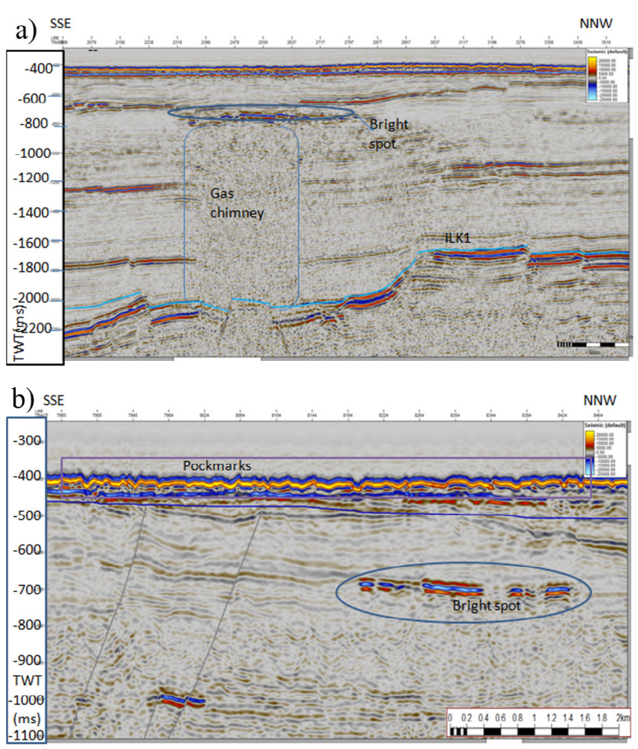

Figure 7: (a) Bright spot, gas chimney and (b) pockmarks.

leakage along the deep sited faults. Locally chaotic reflectors in this part can be good indicators for the subsidence and collapse of the graben structure. One can speculate the graben formation at the middle of the basin may be related with the subsidence of the footwall on both sides of the master faults of the Asterias Fault Complex and Troms-Finnmark Fault Complex. Deep seated faults and vents over the Snøhvit gas field are causing the hydrocarbon leakage which are manifest by pockmarks near and on the seabed [2,8,28]. The folded strata of the Asterias Fault Complex could suggest the nature of the sudden change of the dip of the master fault at depth and dragging of the hangingwall strata along the fault plane.

2D petroleum system modelling

Heat flow calibration: The heat flow of this model ranges from low to average heat flow as confirmed in this model i.e., 41-55 mW/m^2. The discrepancy in well 7120/12 between the observed temperature data and modelled temperature gradient suggests a recent perturbation in the basins thermal regime during the Cenozoic [3]. Thus, the calibration is not possible using a simple heat flow model. Which means as an increase in heat flux to match present-day temperatures forces the model to overestimate maturity. It indicates that the Hammerfest Basin is in a state of thermal disequilibrium, with the Snøhvit gas field is approximately 20°C above norm at the present day [3]. It is possible to infer that there was heat flow variation in the northern and southern parts of the basin. The thermal maturity difference in the northern and southern parts of the basin indicates that the heat flow modelling should consider the uplift/subsidence history. Many models have been tested with different erosion scenarios, fault properties and heat flows and has been observed that the accumulations also vary with these parameters.

Deposition and erosion: The rate of deposition in time and space is variable in the basin. There was rapid burial during Permian (Lopingian and Guadalupian) and late Cretaceous followed by uplifts. Three episodes of erosion (uplift) in the late Cretaceous, Oligocene–Miocene, due to tectonic uplift and Plio–Pleistocene glacial erosion events have been modelled in the basin affecting the hydrocarbon generation, accumulation, maturation and migration (Figure 8). This may be related to uplift and subsidence events. Different scenarios of erosion and uplift have been tested. Finally, three phases of erosion have been considered for modelling. 200 m of Kveite Formation and 300 m Torsk Formation have been eroded due to the tectonic uplift during 75-60 Ma and 30-15 Ma, respectively. The erosion event was continued during Pliocene-Pleistocene (2.5-0.01 Ma) causing the erosion of 100 m thickness of Torsk Formation (Figure 9).

Hydrocarbon generation, accumulation and source rock maturity: Existence of appropriate source rock, and temperature and pressure condition is necessary for hydrocarbon generation in sedimentary basins. The hydrocarbon generation balance of the Hekkingen Formation is very high as compared to the Snadd and Kobbe source rocks but it is migrated upward by leakage. The accumulations in the reservoirs are from the Snadd and Kobbe Formations. On the other hand, this may also indicate that the Kobbe and Snadd Formations may be the major sources of gaseous hydrocarbon accumulation in the reservoirs. Then accumulations in the reservoirs become constant during that time. This is associated with tectonic uplift and erosion of

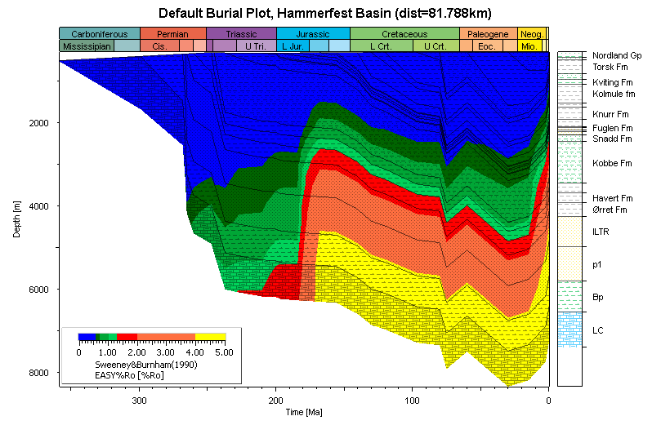

Figure 8: Burial history graph of the Hammerfest Basin superimposed with maturity (Ro) at 81 km.

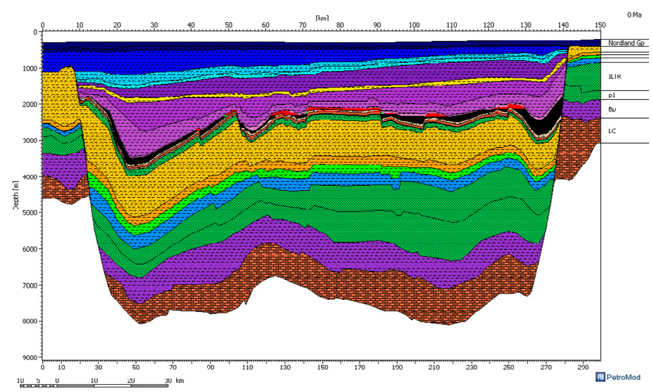

Figure 9: Present day model of Hammerfest Basin and hydrocarbon accumulations in the Stø and Tubåen reservoirs.

the basin during Oligocene. It increases during Miocene and decreases again during Pliocene. The expansion of the gaseous phase causes spilling of oil out of the structures and affected primarily the liquid phase [12]. The hydrocarbon accumulation in each reservoir indicates that the Stø reservoir has a good reservoir potential and it is the main reservoir in the basin. The modelling result shows that the Tubåen reservoir has relatively small accumulations of hydrocarbon. The location of the accumulations has also been confirmed by well 7120/1-2 on the Aterias Fault Complex and 7121/7-2 at the middle of the basin. The Snadd and Kobbe Formations are thermally mature to highly mature which have entered the gas window, whereas the Hekkingen Formation is in the wet gas window to late oil window in the northern part and late oil to main oil windows in the southern part of the Hammerfest Basin (Figure 10 and Table 3). The maturation of the Hekkingen source rock has been interrupted during the uplift/subsidence phases. The increase in depth of burial and heat flow are also the main factors for maturation. The Permian Formations are highly to over mature.

Hydrocarbon migration and leakage: The migration pathway indicates upward and lateral migration across and within the formations (Figures 11 and 12). The upward migration is very dominant in the fault zones, along the Jurassic faults. The Hekkingen source rock has no downward migration pathways to the reservoirs. The closed fault type has more accumulation than the open type faults. But the migration and leakage were realized on both types of model have no big differences. Finally, the AFC and TFFC were defined as closed and the other faults are open which gives the best result in terms of accumulation. Different models have been tested in order to understand the dominant migration pathways. In most of the models the migration direction and leakage to the surface is related to the deep seated faults and the graben structure. Evidence from the seismic profiles includes fluid flow features such as gas chimnies and bright spots located at the crest of the graben. The oil migration follows the deep seated faults along the Asterias Fault Complex, Troms-Finnmark Fault Complex and along the bounding faults of the graben structure at the center of the basin which leads to leakage (Figure 11). The migration of gas on the other hand, is vertically upward throughout the basin leaking out of the seal (Figure 11). This could indicate that the seal is only effective for oil and not for the gas.

Conclusions

The hydrocarbons in the Hammerfest Basin are mainly gas and oil generated from the Hekkingen, Snadd and Kobbe Formations. The hydrocarbons generated from Snadd and Kobbe accumulated mainly in the Stø reservoir while some gas migrated into the Tubåen reservoir.

The Snadd and Kobbe Formations are thermally mature to highly mature and have reached the gas window. On the other hand, the Hekkingen Formation is less mature and it is in the wet gas window to late oil window in the northern part and late oil to main oil windows in the southern part of the Hammerfest Basin. The northern parts of the Hammerfest Basin have subsided more than the other parts. Hence, source rocks in the northern parts are more mature than the central and southern parts of the basin and showing lateral variations in maturation of source rocks.

Hydrocarbon migration from the Snadd and Kobbe source rocks into the Stø and Tubåen reservoirs is dominantly upwards assisted by the faults while the migration from Hekkingen source rock is upward to the Knurr Formation and the migration vector shows that it has no hydrocarbon contribution down to the reservoirs.

The first phase of erosion (75 to 60 Ma) erodes 200 m of Kveite Formation and the second (30 to 15 Ma) and the third erosion (2.5 to 0.01 Ma) phases erodes 300 m and 100 m of Torsk Formation, respectively. Thus, the uplift and subsidence events have been the main factors controlling the hydrocarbon maturation and distribution within the Hammerfest Basin.

Hydrocarbon window	VR	Depth (km)
Early oil window	0.55-0.70	1.9-2.1
Main oil window	0.70-1.00	2.1-2.3
Late oil window	1.00-1.30	2.3-2.5
Wet gas window	1.30-2.00	2.5-3.1
Dry gas window	2.00-4.00	3.1-4.4

Table 3: Oil and gas windows and vitrinite reflectance (VR) which is taken at the middle of the basin.

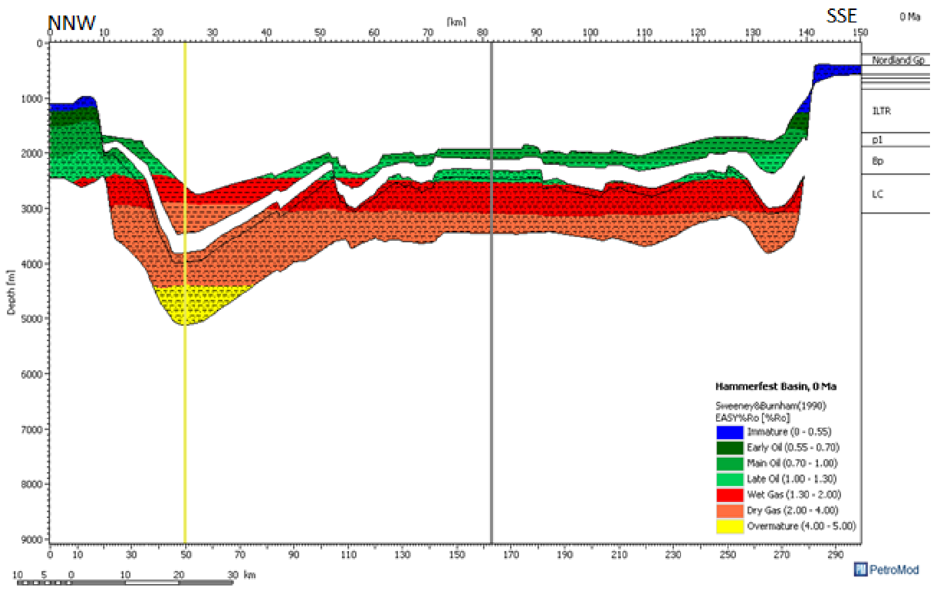

Figure 10: Source rock maturation variations in the southern and northern parts of the basin. Maturity increases toward the northern part of the basin.

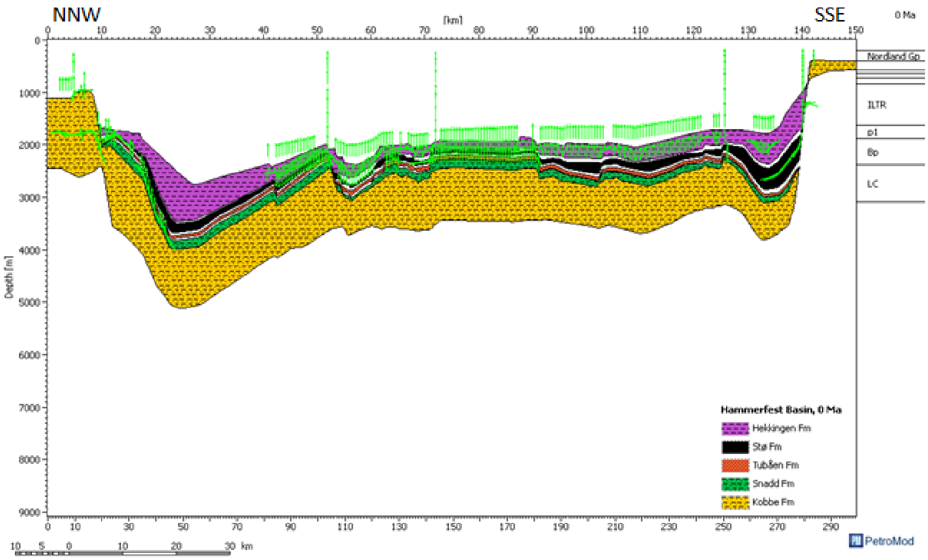

Figure 11: Oil upward migration from the source rocks into the reservoirs and the lateral migration within the source rocks. Further migration of oil out of the reservoir and leakage to the seabed follows the AFC, TFFC along the boundary faults of the graben structure.

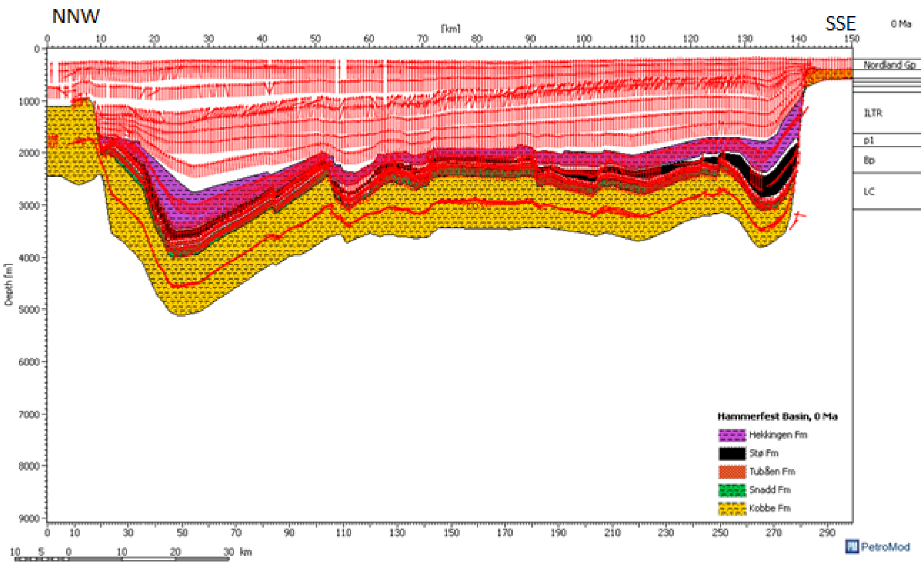

Figure 12: Gas upward migration from the source rocks into the reservoirs and the lateral migration within the source rocks. Further upward migration out of the reservoirs and leakage to the seabed throughout the basin is observed.

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