Chapter 17

Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems

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Abstract: A regional net erosion map for the greater Barents Sea shows that the different areas in the Barents Sea region have been subject to different magnitudes of uplift and erosion. Net erosion values vary from 0 to more than 3000 m. The processes have important consequences for the petroleum systems. Reservoir quality, maturity of the source rocks and the migration of hydrocarbons are affected by the processes. Owing to changes in the PVT conditions in a hydrocarbon-filled structure, uplift and erosion increase the risk of leakage and expansion of the gas cap in a structure. Understanding of the timing of uplift and re-migration of hydrocarbons has been increasingly important in the exploration of the Barents Sea.

Ideas on uplift in the Barents Sea region can be traced back to Fritjof Nansen (1904). During his expeditions in the Barents Sea he concluded from bathymetric investigations that the area had been quite recently uplifted. A renewed focus on this issue in the Norwegian Barents Sea took place after the drilling of the first exploration wells in the early 1980s. Since then, numerous articles discussing uplift have been published. The *Norwegian Journal of Geology* (Vol. 72, no. 3, 1992) gave a status of the discussions along the Norwegian shelf. Some major publications from that time discussing the Barents Sea are: Eidvin & Riis (1989), Vorren *et al.* (1991), Nardin & Røssland (1992), Nyland *et al.* (1992), Riis & Fjeldskaar (1992), Riis (1992), Vågnes *et al.* (1992), Richardsen *et al.* (1993) and Sættem *et al.* (1994). More recent studies have increased our understanding further: Doré & Jensen (1996), Riis (1996), Grogan *et al.* (1999), Doré *et al.* (2000, 2002), Brekke *et al.* (2001), Ryseth *et al.* (2003), Cavanagh *et al.* (2006), Ohm *et al.* (2008) and Anell *et al.* (2009).

Understanding the uplift and erosion history of sedimentary basins plays a central role in the evaluation of prospectivity. Several models have been used to try to calculate the maximum burial depths based on different methods (Cavanagh *et al.* 2006 and references therein). Taking account of the magnitude of uplift and erosion and the timing of such processes is, for some areas, crucial for exploration activity to succeed. Many hydrocarbon basins worldwide have been considerably uplifted through geological time, as most of the world petroleum reserves are located onshore. A compiled subcrop map below Quaternary sediments in the Barents Sea illustrates that the different areas have been subject to different magnitudes of erosion (Figs. 17.1 & 17.2). Net erosion is defined as the difference between maximal burial and the present day burial depth for a marker horizon. The processes may, however, occur in several stages. The principles and the results of the net erosion processes are illustrated by conceptual profiles from the Barents Sea (Figs 17.3 & 17.4).

For some structures the removal of overburden has led to the leakage of hydrocarbons, causing the emptying of reservoirs or structures not being filled to spill. For other structures the main impact has been changes in oil v. gas and PVT ratios. A comparison of the Barents Sea with other areas subject to uplift and erosion processes indicates that the negative effects of these processes may

have been over-stressed (Doré & Jensen 1996; Ohm *et al.* 2008). The effects of uplift (former deeper burial) on reservoir properties and hydrocarbon migration were described by Bjørkum *et al.* (2001).

In most of the Barents Sea wells the upper section (most of Palaeogene and the entire Neogene section) is absent (Figs 17.1 & 17.2). The reservoir quality at a particular depth is generally lower than expected and it has also been noticed that the source rocks are more mature than expected from present temperature gradients and burial depths (Doré *et al.* 2002; Ohm *et al.* 2008). Other observations in the area are that none of the discoveries in the Norwegian and Russian parts of the Barents Sea seem to be filled to spill and that most wells in the Norwegian sector contain traces of oil below the present hydrocarbon–water contact (Nyland *et al.* 1992) and some above the present gas–oil contacts. These features demonstrate that erosion and uplift have had a great effect on the petroleum systems and hydrocarbon accumulations in the area.

Petroleum provinces with uplift

Examples of prolific petroleum provinces that have been uplifted during the Cenozoic to compare with the greater Barents Sea region are listed in Table 17.1. In more detail, the Western Canada and Sverdrup Basins seem to represent good analogues to the Barents Sea. Table 17.2 shows their similarities in geological development. The magnitudes of uplift are estimated to be similar in amounts to the Barents Sea, but there are large differences in the numbers of wells drilled and their proven reserves.

Measuring net erosion and its effect on petroleum accumulations

The differences between uplift and net erosion have often not been appreciated. They were previously described by Bjørnseth *et al.* (2004). Figure 17.4 illustrates the main differences.

Several methods can be used to estimate uplift and net erosion using well data (Figs 17.5 & 17.6 and Table 17.3). An average

Fig. 17.1. Compiled regional subcrop map below Quaternary for the Barents Sea region. Based on information from Norwegian Petroleum Directory (NPD) Sevmorneftegeofisika (SMNG) and this work. There is a clear correlation between the subcrop of older rocks below the base Quaternary unconformity (along mainland and Novaya Zemlya) and the areas with major uplift and net erosion.

Fig. 17.2. Regional geoseismic profile running from the Atlantic Margin to Yamal (modified from Stoupakova *et al.* 2011). The profile illustrates the basin configuration and areas with shallow basement in the Barents Sea. Areas with missing section and major erosion can be identified several places along the profile. The erosional products of the Cenozoic uplift phases can be seen in the Palaeogene and Neogene wedges to the west. In the Barents Basin massive sill intrusions are identified. For location see Figure 17.1.

Fig. 17.3. Geo-seismic profile from the western Barents Sea, illustrating areas with increased uplift and net erosion to the east.

standard deviation based on statistics can be estimated. It is interesting to notice that the standard deviation narrows with increasing numbers of methods.

In areas without well control, other methods can be used, for example evaluation of seismic velocities, seismic stratigraphical analysis and/or structural modelling. These methods normally give a good indication of the relative variation in net erosion and can be used to contour net erosion between wells. However, if well data are sparse, there will be a high uncertainty in net erosion estimates.

The relationship of uplift and net erosion to the elements affecting petroleum prospectivity are summarized in Figure 17.7 and Table 17.4. The consequences and the effects of uplift and net erosion through geological time are particularly important to consider in prospect evaluation, as illustrated in Figure 17.8. Statistics

show that most of the discovered hydrocarbons occur in reservoir rocks within the temperature range of approximately 60–120 °C (Bjørkum *et al.* 2001).

Estimates of net erosion in the Barents Sea region

Evaluating the effect of uplift and erosion is a challenge recognized by the oil companies. Underfilled structures, oil staining in reservoirs below present oil water contacts and potential remigration of hydrocarbons have been observed and discussed in recent decades (Nyland *et al.* 1992; Doré *et al.* 2000). A compilation of studies done 20 years ago shows a similarity of the general uplift/net erosion trends (Fig. 17.9). However, the magnitude of uplift for some specific points varies from 0 to 500 m. A more detailed map based on seismic velocities (Richardson *et al.* 1993) shows the same general trend but indicates that local variation of net erosion can be significant. The lower-frequency map constructed by Ohm *et al.* (2008) is also in agreement with the general net erosion trends, based on vitrinite data. However, differences between net erosion maps based on single methods still exceed 500 m in several areas. The amounts of the uplifts of the Norwegian mainland in Cretaceous, Palaeogene and Plio-Pleistocene periods (Riis 1996) indicate the complexity of constructing a net erosion map and discussing the timing of the major events.

Based on available geological and geophysical data, an extensive study of uplift and net erosion has been carried out for the greater Barents Sea and a regional net erosion map has been constructed (Fig. 17.10). The confidence in this study is in general high to the west, especially in the Hammerfest Basin, where many wells have been investigated in detail, and several methods were used in order to narrow the standard deviation. In other areas less data have been available and the map is consequently more speculative. In the Russian Barents Sea vitrinite reflectance data and tectono-stratigraphical analyses from seismic data provide the background for constructing the map.

Svalbard, Novaya Zemlya and the Norwegian mainland have been much affected by uplift and net erosion. However, due to significant changes in the lithification of Mesozoic sandstones on the eastern side of Svalbard archipelago (G. B. Larssen pers. comm.), high local variation in net erosion might be expected. The interpretation in the area can therefore be confused with the effect of local variation in heat flow due to intrusive sills and dykes (Fig. 17.11), as seen in the Svalbard area (Grogan *et al.*

Fig. 17.4. Sketch showing the principal differences between uplift, erosion and net erosion.

Table 17.1. Comparison of Petroleum provinces with Cenozoic uplift. Modified from Doré & Jensen (1996) and references therein

Basin	Country	Main reservoir age	Main source rock age	Timing uplift/net erosion	Nature of uplift
San Juan	USA	Cretaceous Permian Carboniferous	Cretaceous Carboniferous	Late Eocene–Recent	Epeirogenic–isostatic
Permian	USA	Permian	Carboniferous Permian	Cretaceous–Recent	Epeirogenic–isostatic
Maracaibo	Venezuela	Miocene Oligocene Eocene	Cretaceous	Early Miocene– Late Eocene	Orogenic
Zagros Foreland	Iran	Cretaceous Miocene Oligocene	Cretaceous	Miocene–Recent	Orogenic
Jungar	China	Jurassic Carboniferous	Jurassic, Triassic, Permian	Miocene–Recent	Orogenic
Western Canada	Canada	Cretaceous Devonian	Jurassic/Cretaceous Triassic Carboniferous Devonian	Oligocene–Recent	Post Orogenic Epeirogenic–isostatic
Timan Pechora	Russia	Triassic Permian Carboniferous Devonian	Permian Devonian Silurian	Miocene/Pliocene Jurassic	Orogenic–isostatic
Barents Sea	Norway	Jurassic/Cretaceous–Triassic Carboniferous/Permian	(Upper Jurassic) Triassic Middle Permian	Palaeogene and Neogene	Orogenic–Isostatic

Table 17.2. Comparison between arctic uplifted areas: Western Canada Basin (modified from Doré & Jensen 1996, and references therein), Sverdrup Basin (Arne et al. 2002; Harrison et al. 1999) and the Barents Sea

	Western Canada Basin	Sverdrup Basin	Barents Sea
Basin type	Platform, bordering major Jurassic–Cretaceous foredeep orogen and craton	Cenozoic Orogeny Carboniferous-rifted basin Lower Palaeozoic foreland basin	Platform, bordering major Permo-Triassic foredeep/orogen, craton and ocean margin
Source rocks	Upper Cretaceous (oil) Lower Cretaceous (gas) Lower Jurassic (oil) Triassic (oil/gas) Lower Carboniferous (oil) Middle/Upper Devonian (oil)	Cenozoic? (oil) Upper/Middle Triassic (oil/gas) Devonian? (oil)	Upper Jurassic Lower Cretaceous (oil) Lower/Middle Jurassic (gas) Lower/Middle Triassic (oil/gas) Permian-postulated Lower Carboniferous-postulated Middle Devonian SE-area (oil)
Sediment types	Permian–Cenozoic: siliciclastic Devonian–Carboniferous: carbonate, evaporite, siliciclastic	Cenozoic siliciclastic Mesozoic siliciclastic Mesozoic sill intrusions Carboniferous carbonates, evaporites and redbeds	Lower Permian–present: siliciclastics Carboniferous–Lower Permian: carbonates, evaporites, siliciclastics
Cenozoic uplift (net erosion?)	1000–4000 m	1000 m?	1000–3000 m
Suggested uplift mechanisms	Uplift related to opening of the Arctic Ocean Post-orogenic isostatic uplift Post-glacial rebound	Eureka orogeny (Paleocene/Eocene) Sub-lithospheric underplating (Eocene)	Uplift related to opening of Atlantic and Arctic Oceans Compression and/or transpression Isostatic response to sediment unloading Post-glacial rebound
Glaciation	Heavily glaciated, major continental ice sheets during last glaciation	Heavily glaciated, major continental ice sheets during last glaciation	Heavily glaciated, major continental ice sheets during last glaciation
Area 10 ⁶ km ²	1.3	0.52	1.3
Number of wells drilled	c. 200 000	c. 180	c. 140 (total Barents Sea including Pechora Sea)
Proven oil reserves	2.23 × 10 ⁹ S m ³ (+480 × 10 ⁹ S m ³ oil in place in Alberta tar sands)	540 × 10 ⁶ S m ³ (in place volume)	Norwegian Barents: c. 150 × 10 ⁶ S m ³ (all in place volumes) Pechora Sea: 700 × 10 ⁶ S m ³
Proven gas reserves	2600 × 10 ⁹ S m ³	500 × 10 ⁹ S m ³ (in place)	Norway: 260–300 × 10 ⁹ S m ³ recoverable Russia: greater than 3500 × 10 ⁹ S m ³

Fig. 17.5. Spread in magnitude of net erosion in the Barents Sea based on different methods and several wells. Each data point represents a net erosion estimate from one single method in a specific well (y-axis) plotted against the average estimate from several methods in the same well (x-axis). (a) The net erosion estimates from the Pyrolyse T-Max method (yellow area) plot systematically outside the range from other methods. (b) Therefore T-Max is not recommended to be used and is not included in the average net erosion calculations.

1999), on Franz Josef Land and in the Eastern Barents Sea (Gramberg *et al.* 2001). Increased net erosion on structural highs (e.g. on the Central Barents Sea High and on Admiralty High)

Fig. 17.6. Example of a Monte Carlo simulation run on data from one well in the Barents Sea, showing net erosion estimate distribution curves. The weighted average distribution is based on all the single methods, but these are weighted due to the quality of input data and the overall confidence of each method.

may coincide with areas affected by compressional or transpressional tectonic regimes related to the opening stages of the Atlantic and the Arctic Oceans (Faleide *et al.* 1993; Doré & Lundin 1996). Certain areas on Spitsbergen may have been buried more than 3000 m deeper than at present (previously suggested by NPD 1996), whereas the magnitude of net erosion was probably a little less on Novaya Zemlya. The subcrop of older rocks below base Quaternary along the Norwegian and Russian mainland as well as along Svalbard and Novaya Zemlya (Figs 17.1 & 17.2) coincides with areas of highest expected net erosion (Fig. 17.10). The deeper basins are less eroded. The South Barents Basin may have undergone less than 500 m of net erosion, whereas in the

Table 17.3. Methods used to assess the magnitude of uplift based on well data, with estimated uncertainty level

Method	Standard deviation (m)
Shale compaction, density logs	150
Shale compaction, sonic logs	150
Vitrinite reflectance	220
Sandstone diagenesis	220
Apatite fission track analysis (AFTA)	220
Pyrolysis T-Max: not recommended to use

Fig. 17.7. Relationship of uplift and net erosion to the elements affecting petroleum prospectivity.

Norwegian sector, the sedimentary basins indicate net erosion values between 900 and 1400 m (Figs 17.3 & 17.10). The change of net erosion along the central axis of the Barents Sea (Fig. 17.10) may coincide with a north–south basement-related structure trend (Henriksen *et al.* 2011). Further to the west a zero line, where no net erosion has occurred, is suggested.

The timing of the major uplift and erosion periods has been a discussion for many years. In the Barents–Kara Sea area evidence of several tectonic events has been described (Gabrielsen *et al.* 1984, 1993, 1997; Vågnes *et al.* 1992; Faleide *et al.* 1993; Anell *et al.* 2009). It is generally agreed that a late Neogene isostatic uplift affected the whole region (Vorren *et al.* 1990; Riis & Fjellskar 1992; Eidvin *et al.* 1993; Cavanagh *et al.* 2006). Compressional and transfer movements during Palaeogene time have affected areas around the Atlantic Margin and on Svalbard (Doré & Lundin 1996; Faleide *et al.* 1996; Vågnes 1997; Brekke *et al.* 2001; Ohm *et al.* 2008). It seems likely that the Central Barents High and Novaya Zemlya were affected by these movements, which led to uplifted areas (Fig. 17.10). Although most areas have experienced multiple phases of uplift, not all of them are contributing to the net erosion. For example areas affected by the major uplift during Late Jurassic to Early Cretaceous time were probably buried deeper after the Jurassic/Cretaceous erosion. The timing of maximum burial is important in the evaluation of source rock maturity and migration (Riis 1996; Doré *et al.* 2000, 2002; Cavanagh *et al.* 2006; Ohm *et al.* 2008). Different areas in the Barents Sea achieved maximum burial at different times. High areas affected by Palaeogene uplift and erosion might not have seen deeper burial after the Palaeogene tectonics, while in basin areas continuous sedimentation may have occurred until glacial erosion in Plio-Pleistocene times.

Effects on reservoir quality

Reservoir properties, in particular porosity, change in relation to increasing burial depth and reservoir temperature. Studies from the North Sea basins and the mid-Norwegian continental shelf suggest that the primary driving mechanisms are compaction at shallow depths, followed by precipitation of authigenic quartz cement as the temperature exceeds a threshold value of about 60 °C. For instance, Jurassic sandstones in the Haltenbanken area show a porosity reduction of about 8–9% per kilometre overburden (e.g. Ehrenberg 1990; Ramm & Bjørlykke 1994).

Table 17.4. Effects due to uplift and erosion

Process	Uplift	Net-erosion
Reservoir quality		×
Reduction in hydrocarbon generation rates		×
Change of drainage pattern through time	×	
Fracturing of cap-rock	×	×
PVT changes in the reservoirs		×
Fault reactivation	×	×

Fig. 17.8. Diagram to illustrate the effect of uplift on structures and the consequences for generation, migration and trapping of hydrocarbons.

Early studies of diagenetic processes in the Jurassic reservoir rocks in the Hammerfest Basin (Olaussen *et al.* 1984) showed that quartz cement is the major porosity-reducing agent in these sandstones. Furthermore, the studies also showed that solution of quartz grains and extensive stylolization has occurred, along with illitization of kaolins, at present day burial depths in the 2–2.5 km range. Elsewhere on the Norwegian continental shelf, such processes are seen at much deeper levels, generally at 3.5 km and deeper, suggesting that the reservoir rocks in the Hammerfest Basin have experienced deeper burial and higher temperatures than today.

Subsequent petrographic studies (e.g. Walderhaug 1992) have confirmed that the Barents Sea has undergone severe uplift and erosion (Fig. 17.10). Uplift estimated from reservoir properties in the Hammerfest and Nordkapp basins ranges from about 500 m in the west to about 1500 m to the east. Furthermore, uplift exceeding 1.5–2 km has been inferred for part of the Bjar-meland Platform. Accordingly, any prediction of reservoir quality (porosity) should take account of the maximum burial prior to uplift.

Figure 17.12 illustrates a porosity–depth relationship based on core data for Late Triassic–Jurassic sandstones in the Norwegian Barents Sea. The plotted trend line is based on data from Middle Jurassic sandstones on the mid-Norwegian shelf (Halten Terrace) to the south, where no uplift/erosion has been inferred (Ramm & Bjørlykke 1994). These sandstones are of similar petrographic composition (typically sub-arkoses) to their Barents Sea equivalents, and provide a very reasonable comparison.

Porosity plotted v. present overburden (Fig. 17.12a) yields a weak depth trend and general loss of porosity with increasing depth. However, the plot does not give a good comparison with the trend line from the mid-Norway shelf. When restoring the porosity measurements to the inferred maximum burial depths (Fig. 17.12b), a more reasonable fit with the mid-Norwegian shelf data is established. In essence, the better sandstones in the Barents Sea basins appear to fall on the reference trend, with a general porosity reduction of about 8% per km. For instance, data from Well 7125/1-1 show about 20–25% porosity at a present day burial of approximately 1200 m relative seafloor, which is significantly lower than at similar depths on the mid-Norway shelf. When these data are shifted down to a maximum burial exceeding approximately 2500 m (inferring 1300 m uplift/erosion), the porosity values fit with the established mid-Norway trend.

The plots can be used for assessing realistic porosity ranges for the relevant formations in a given exploration prospect, once the actual uplift in the particular area has been estimated. However, possible variations related to different petrographic compositions

Fig. 17.9. Previous uplift maps for the western Barents Sea indicating a common general trend of uplift and net erosion, increasing towards east and north. In some areas rather large differences in the estimates are observed. More recent work, using a single method for uplift and net erosion, still shows discrepancies up 500–600 m.

and variable thermal gradients have not been addressed here, although it is noted that a lower thermal gradient dominates, for instance, in the South Barents Basin (Henriksen *et al.* 2011). Also, the large porosity range seen in the available core data is in part controlled by grain size variations and depositional facies, with the low-porosity tail values reflecting nonreservoir. Under certain conditions, however, the porosity loss induced at deep burial may be inhibited. In particular, grain-coating agents such as chlorite and other clay minerals may prevent quartz from precipitating, thus preserving porosity and permeability at deep burial depths (e.g. Ehrenberg *et al.* 1998). Such mechanisms are also seen in the Triassic strata in the Barents Sea, for which separate porosity–depth relationships must be developed.

Effects on seal capacity

The impact of uplift and net erosion has been a concern with respect to preservation of oil and gas in the Barents Sea reservoirs. The top seal is assumed to be greatly affected in inverted basins and catastrophic failure can occur (Doré *et al.* 2000). The fact that oil staining is observed far below (100 m) present oil–water contact in the Snøhvit field is believed to be a result of gas expansion and oil spill due to uplift and pressure reduction (Nyland *et al.* 1992; Skagen 1993). Has it all then leaked? Obviously not! Some major discoveries have been made, for example Shtokmanovskoye (gas–condensate) and Prirazlomnoye (oil) in the Russian Barents Sea and the Pechora Sea. The more modest Snøhvit (gas–oil) and Goliath (oil) discoveries clearly demonstrate working petroleum systems in the Norwegian sector, in areas that have experienced around 1000 m net erosion (Fig. 17.10). Since most structures naturally are leaking, the emptying of structures is a balance between the migration of hydrocarbons into traps v. the natural leakage. Episodic discharge of methane in the Hammerfest Basin due to the many Weichselian oscillations has been modelled (Cavanagh *et al.* 2006). If then the hydrocarbon generation has stopped due to uplift and cooling, the result will be the partial or

complete emptying of traps. However, as pointed out by Doré *et al.* (2002) and Ohm *et al.* (2008), redistribution of the hydrocarbons may take place and potentially charge traps in more distal locations. In order to understand the remigration of hydrocarbons, assessing uplift and net erosion is crucial to exploration.

Traps which are not fault-bounded, that is either stratigraphic or anticline traps, are believed to have a higher ability to ‘survive’ uplift. Salt-related structures, for example in the Nordkapp, Tromsø and Tiddlybanken basins, are assumed to be robust even in areas with considerable uplift and erosion. Exploration drilling has demonstrated trap failure in some areas where the seal is dependent on extensional faults. In the Pechora Basin though, fault-bounded structures with compressional faults reaching the surface (Henriksen *et al.* 2011) are sealing. The lithology and nature of the cap rock is important. It has been noted that the sealing rock does not need to be very thick. A study of data from the Hammerfest Basin indicates that there is no correlation between the thickness of sealing rock and the hydrocarbon column height that was observed in the wells. In the Nordkapp Basin the first well (7228/7-1) discovered oil and gas in the Triassic section. Based on pressure gradients in the well, three internal seals can be seen, represented by thin shales. The evaluation of each prospect should involve thorough leakage studies because many local factors have to be considered.

Effects on petroleum generation, migration and biodegradation

The maturation of source rocks is an irreversible process, implying that an observed/measured maturity parameter reflects the maximum temperature that the source rock has seen (Bjørkum *et al.* 2001). Time also affects maturity development, but source rock kinetics is much more sensitive to temperature than to time. It is assumed that the Hammerfest Basin at present is in significant thermal disequilibrium due to the rapid late Cenozoic uplift (Cavanagh *et al.* 2006).

Fig. 17.10. A regional map illustrating the estimated net erosion for the Greater Barents Sea. In the west (Atlantic Ocean) there has been no erosion, only subsidence. Over the entire Barents Sea region net erosion ranges from zero to >3000 m.

In the Barents Sea in general, matured source rocks are observed much shallower than expected from vitrinite measurements, and consequently the rock has experienced higher temperature pre-uplift. An uplifted, oil mature source rock, for example with measured Vitrinite Reflectance of 0.7%, will have started to generate hydrocarbons at maximum burial depth, but with reduced temperature due to uplift, the hydrocarbon generation will have ceased (Doré *et al.* 2000; Ohm *et al.* 2008). This is an effect that could lead to limited charge to prospects and would especially affect prospects that are dependent on late charge due to late trap formation.

In uplifted areas migration pathways can change significantly from the times of maximum burial to present day. As maximum burial estimates are not precise numbers (often $\pm$ several hundred metres) and because distances between the data points in the Barents Sea are large, there will be large uncertainties connected to how migration patterns have changed during uplift and erosion.

Gas expansion due to pressure release and changes in hydrocarbon phase due to change in PVT conditions (gas release from oil, if the oil is saturated at maximum burial) can be a consequence of uplift/erosion. This is an effect observed in the Hammerfest Basin and the Snøhvit field is often mentioned as an example of

this (Nyland *et al.* 1992; Skagen 1993; Cavanagh *et al.* 2006). A secondary effect of gas expansion in a two-phase reservoir is spill of oil laterally. This occurs when the oil is forced down below the spill-point (valid if the structure is sufficiently filled) because the gas occupies more of the reservoir volume after uplift and erosion.

About 50% of the oil/residual oil that is found at shallow depths in the Barents Sea wells is biodegraded. Based on new research, the biodegradation risk can be better understood in shallow reservoirs in uplifted and eroded areas (Wilhelms *et al.* 2001). This theory is supported by observations from several oil fields worldwide and claims that reservoirs exposed to temperatures $>80^\circ\text{C}$ are protected against biodegradation. To evaluate the biodegradation risk in undrilled prospects, it is important to consider the timing of oil generation for the relevant source rocks and to estimate the net erosion. The timing of maximum burial can be given based on Apatite Fission Track data. The timing for uplift and net erosion for several areas is compiled in Table 17.1. Figure 17.11 illustrates the impact of multitectonic events on an area. The consequence of net erosion is that prospective areas are now shallower and at lower temperatures compared with basins without net erosion (Figs 17.10, 17.12 & 17.13).

Fig. 17.11. The effect of sill intrusions on the vitrinite measurements (modified from Gramberg 2001). Examples from onshore Franz Josefs Land, the Murmanskaya and Severo Kildinskaya gas discoveries in the South Barents Basin indicate that the intrusions may have considerable influence on the heat flow locally. The figure illustrates the difference in vitrinite reflectance in areas affected by intrusions (i.e. Murmanskaya) v. areas not affected (Kurentsovskaya).

Fig. 17.12. Porosity v. depth plot for Upper Triassic/Jurassic sandstones in selected released Barents Sea wells (Hammerfest and Nordkapp basins). A trend line for the Haltenbanken area offshore mid Norway is inserted for comparison. (a) Relative to present day seafloor (mRSF) and (b) shifted to maximum burial depth as inferred from uplift/erosion estimates.

Fig. 17.13. Illustration of an area with two compressional events, and net erosion. (a) Present day and (b) prior to tectonic movement and erosion. Position A: no closure before second tectonic movement. Bypass of hydrocarbons. Favourable for migration post structuration and erosion due to mature source-rock in kitchen area. Position B: old trap, favourable for migration pre-second movement. Risk for emptying the trap due to late tectonic movement. Possibility for gas expansion due to removal of overburden, and spill of oil to updip traps. Reduced migration from kitchen area post uplift and erosion. Sensitive to amount of net erosion. Position C: no closure before second tectonic movement. Bypass of hydrocarbons. Unfavourable for migration post structuration due to net erosion and cooling of source-rock in kitchen area. Possibility for receiving oil due to gas expansion in down-flank structures.

Conclusions

Cenozoic uplift and net erosion has been subject to several studies during recent decades. The correlation between the subcrop map and the net erosion map indicate that, as a first approach, the former can be used to predict relative changes in net erosion. In this study several methods have been used to construct the regional net erosion map, showing major differences in the Greater Barents Sea. The confidence varies due to data coverage and quality. By using several methods (where available) in this study, the standard deviation in net erosion estimates is reduced. For more detailed estimations, more work needs to be carried out in order to reduce the uncertainties further and to resolve the local variations that certainly exist.

The greater Barents Sea has experienced different amounts of uplift and erosion that have important consequences for petroleum

systems. This has affected the reservoir quality, source rock maturity/migration and reservoir pressure. Understanding the re-migration of hydrocarbons will be important in order to succeed in future exploration activity. Intrusions that have been observed in several places complicate the interpretation of net erosion further. Except for the western and northern margins of the greater Barents Sea, all areas have been subject to net erosion. This means that the rocks in many areas have undergone a temperature history quite different from what would be expected based on their present depths.

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