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INTRODUCTION

The Barents Sea is situated on the Norwegian and Russian continental shelves, and is bounded by the Norwegian – Greenland Sea, the islands of Svalbard and Novaya Zemlya, and the Norwegian and Russian mainland (Figure 1). Extensional tectonics was the dominant process of deformation in the western Barents Sea, beginning in the Late Devonian-Early Carboniferous time and culminating with the break-up between the Greenland and Norway in Paleocene period. Moreover, the western part of the Barents Sea has been tectonically the most active area throughout Mesozoic and Cenozoic times. The structural evolution of this region since Middle Jurassic comprises two main phases: Late Mesozoic rifting and basin formation and Early Cenozoic rifting and opening of the Norwegian – Greenland Sea (Faleide et. al., 1993). In addition, this period is characterized by significant uplift and erosion in the entire western Barents Sea, especially during Late Cenozoic.

A number of models have been proposed to explain the structural evolution of the south- western Barents Sea during the Late Mesozoic and Cenozoic times (Rønnevik, 1981, Rønnevik & Jacobsen, 1984, Riis et. al., 1986, Faleide et. al., 1984, Gabrielsen et. al., 1990, Dengo & Røssland, 1992, Sund et. al. 1986) (Figure 2). However, there is no unanimous agreement on the subject. Several workers attempted to model Cenozoic uplift and erosion (Riis & Fjeldskaar, 1992, Vågnes et. al. 1992, Reemst et. al., 1994, Clift et. al. 1998, and Cavanagh et. al. 2006). Still, erosion estimates are deviating from one uplift mechanism to another.

Petroleum exploration in the western Barents Sea is about to take a strategic place for future petroleum activity in Norway. It is well known that late phase of erosion in the Barents Sea significantly affected the petroleum accumulations in traps (Nyland et. al., 1992). Therefore, it is highly important to understand causes of erosion in order to deal with consequences.

The southwestern Barents Shelf contains some of the deepest sedimentary basins worldwide, bounded by several highs and platforms (Figure 3). The study area, the Loppa High, is a regional structural high that has a long and complex history dating back to the Carboniferous. It is located north of the Hammerfest Basin and borders with Tromsø and Bjørnøya Basins to the southwest and west, respectively (Figure 3). Several events of erosion

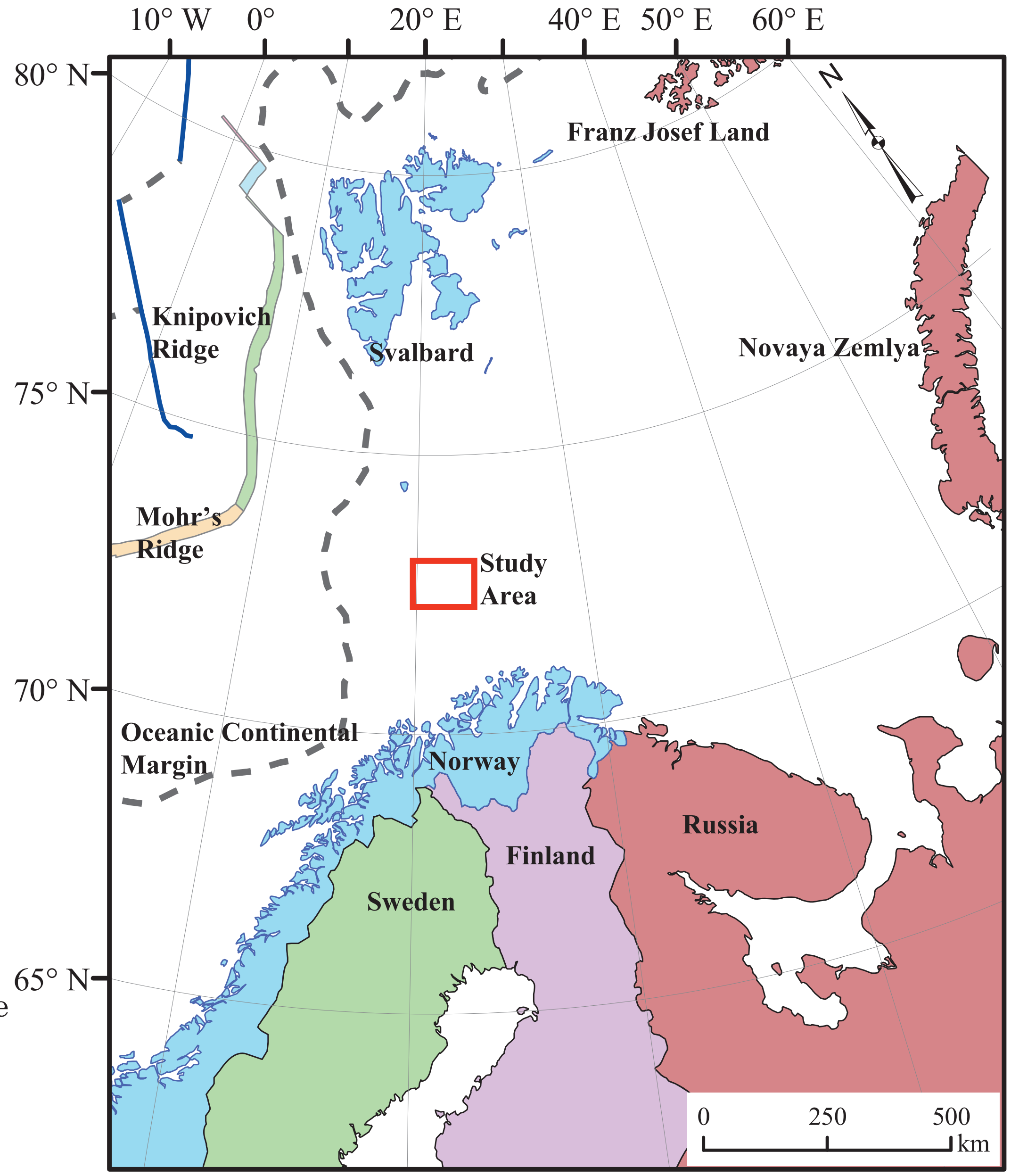


Figure 1. Regional position of the Barents Sea in the North and the study area (red square) between the Norwegian mainland, North Atlantic crust and Svalbard.

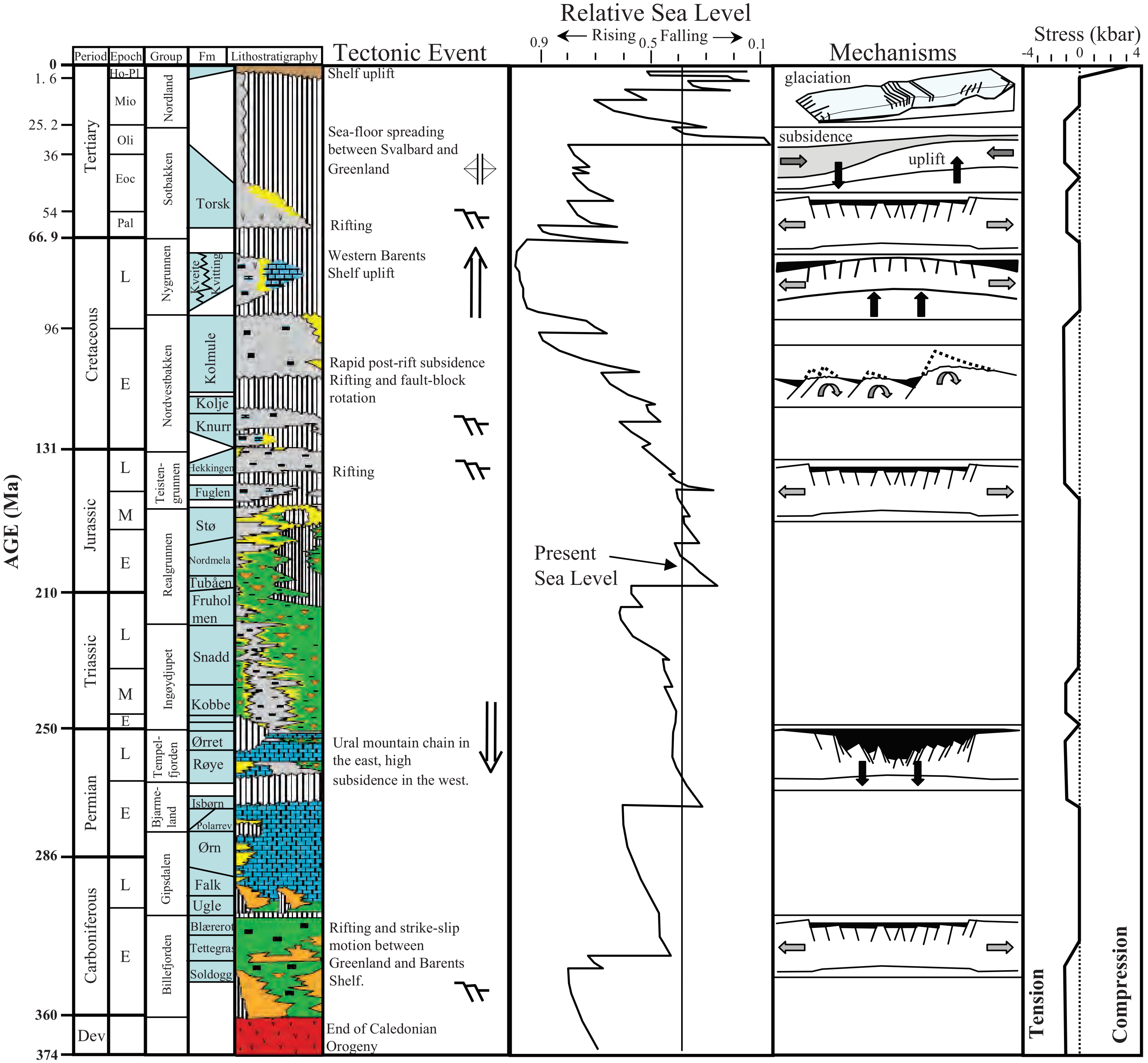


Figure 2. Summary chart showing main tectonic events and its possible mechanisms, global sea-level changes curve and stretching/compression factor. Modified from Worsley, 2006; Rønnevik, 1981; Gabrielsen et. al., 1990; Reemst et. al., 1993; Nøttvedt et. al., 1995.

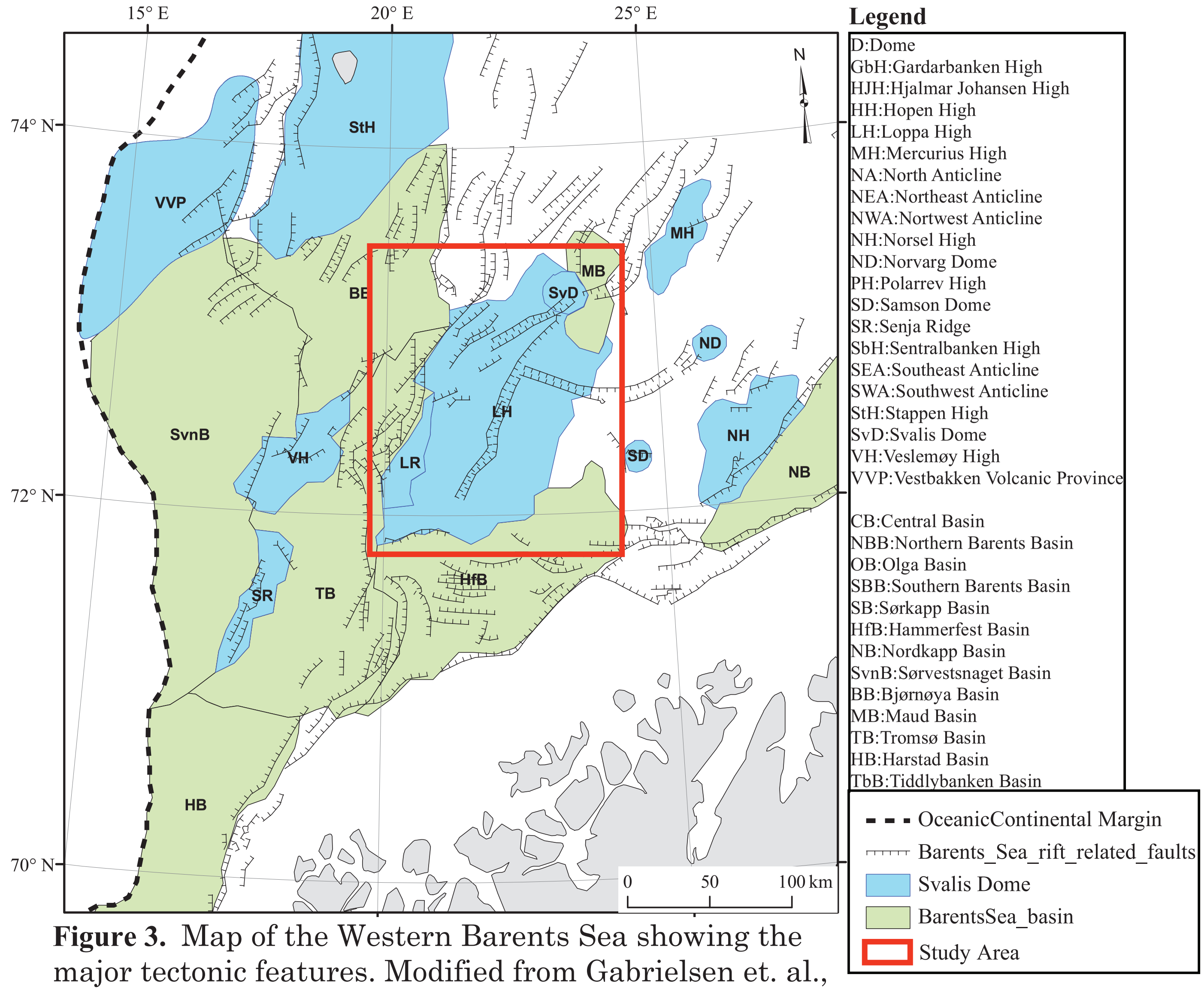


Figure 3. Map of the Western Barents Sea showing the major tectonic features. Modified from Gabrielsen et. al., 1990 and Norwegian Petroleum Directorate (www.npd.no)

as a response to uplift can be observed on the Loppa High. Therefore, a large amount of sediments is lost what makes this area extremely difficult to interpret (Figure 2). However, the Loppa High represents an excellent site for studying and mapping the unconformities at different stages of uplift and estimating erosion. This set of features makes the study area significant for understanding petroleum potential and future exploration in the southwestern Barents Sea.

The purpose of this study is to study the Cretaceous – Cenozoic evolution of the Loppa High and its adjacent basins in order to establish the uplift mechanisms compared with earlier proposed mechanisms and to quantify the erosion.

The main objectives of this thesis are:

- to define the age of erosional surfaces within established stratigraphic sequences or tectonic phases;
- to propose possible causes of erosion and to quantify them.

In order to achieve this, the following steps are ought to be done:

- to interpret the key horizons and to generate time structure and isopach maps to represent the lateral distribution of the different successions;
- to establish major seismic stratigraphic sequences along with main fault families;
- to establish the exact age of major tectonic events that affect the study area.

The study was performed using the integrated dataset of ca. 20 000 km of 2D multichannel seismic profiles combined with 10 exploration wells. The dataset is released to the universities and was provided by Norwegian national petroleum database (Petrobank). Seismic interpretation and map generation was carried out using Landmark’s OpenWorks™ interpretation software package.

GEOLOGICAL SETTING OF THE BARENTS SEA WITH FOCUS ON THE LOPPA HIGH

The Barents Sea is a wide epicontinental basin located north of Norway and Russia on the passive continental margin that developed as the North Atlantic and Arctic oceans opened in response to the break-up between Greenland and Norway in the Late Paleocene (Dengo and Røssland, 1992). It is a rather deep shelf sea (average depth 230 m), bordered by the shelf edge towards the Norwegian Sea in the west, the island of Spitsbergen-Norway in the northwest, and the islands of Franz Josef Land and Novaya Zemlya (Russia) in the northeast and east (Figure 1).

The Barents Sea consists of a complex mosaic of platform areas and basins. The major structural elements of the southwestern part of the region are summarized in Figure 3. As shown in figure 3, the Barents Sea continental shelf is dominated by a system of NE – SW structural trends in the southern and eastern parts that has been influenced by Caledonian (Devonian) trends, whereas the western and northwestern areas are influenced by NNW-SSE trending structures (Rønnevik et al., 1982; Faleide et al., 1984; Rønnevik & Jacobsen, 1984, Dengo & Røssland, 1992, Gudlaugsson et al., 1998). In the southern part, a zone dominated by ENE-WSW trends is defined by major fault complexes bordering the Hammerfest and Nordkapp Basins. This trend is sub parallel to another major zone to the north defined by the Veslemøy High and the fault complexes separating the Loppa High from the Bjørnøya Basin (Figure 3).

The Loppa High is a regional structural high, which is diamond-shaped in outline (Figure 3). It consists of an eastern tilted platform and a crestal western and northwestern margin. Loppa High is associated with positive gravity and magnetic anomalies caused by a relatively shallow metamorphic basement of Caledonian age underlying the western part (Faleide et al. 1993). It is bounded on the south by the Asterias Fault Complex and on the east and southeast by a monocline towards the Hammerfest Basin and Bjarmeland Platform (Figure 3). To the west, the Loppa High is separated from Tromsø Basin by the Ringvassøy – Loppa Fault Complex. The Bjørnøyrenna Fault Complex is located between Loppa High and Bjørnøya Basin (Figure 3). A major salt dome, the Svalis Dome, and its associated rim syncline, the Maud Basin, mark the northeastern limit of the high (Gabrielsen et al., 1990) (Figure 4).

Multiple pre-break-up tectonic events are recorded in the Barents Sea. Several papers have described the geological evolution of the Barents Shelf (Rønnevik, 1981, Rønnevik et al., 1982, Faleide et al., 1984, Rønnevik & Jacobsen, 1984, Faleide et., 1993, Gudlaugsson et. al., 1998, Torsvik et. al., 2002, Brekke & Olaussen, 2008) (Figure 2). The major phases of tectonic events that dominated in the western Barents Sea with focus on the study area are summarized below:

Early Devonian-Early Carboniferous: **(Figures 5A & 5B)**

The Caledonian Orogeny, related to the collision and suturing of Laurentia and Baltica in Early Devonian time, formed the metamorphic basement of the Barents Sea (Dengo and Røssland, 1992). During the Late Devonian, Greenland and Scandinavia were largely centered at the equator (Figure 5A). Erosion of the Caledonian mountain range led to the deposition of thick continental clastic sediments of alluvial fans and river plains into half-grabens, formed during the initial phase of crustal extension between Greenland and Norway (Rønnevik, 1981, Worsley, 2006). As the continent drifted northwards, most of the shelf became a warm-water carbonate platform with organic buildups and deposition of the sabkha evaporites at times of lowstand (Worsley, 2006).

Several workers have proposed (Faleide et al., 1984, Rønnevik and Jacobsen, 1984) that the Late Devonian - Early Carboniferous crustal extension in the western Barents Sea resulted form the combined effect of sinistral strike-slip faulting in the western part of the Barents Sea and conjugate dextral strike-slip in the central Barents Sea (Figure 5B). Moreover, this period was characterized by thick-skinned, normal large - scale block faulting. Most of the known major structural trends have been established by Devonian times.

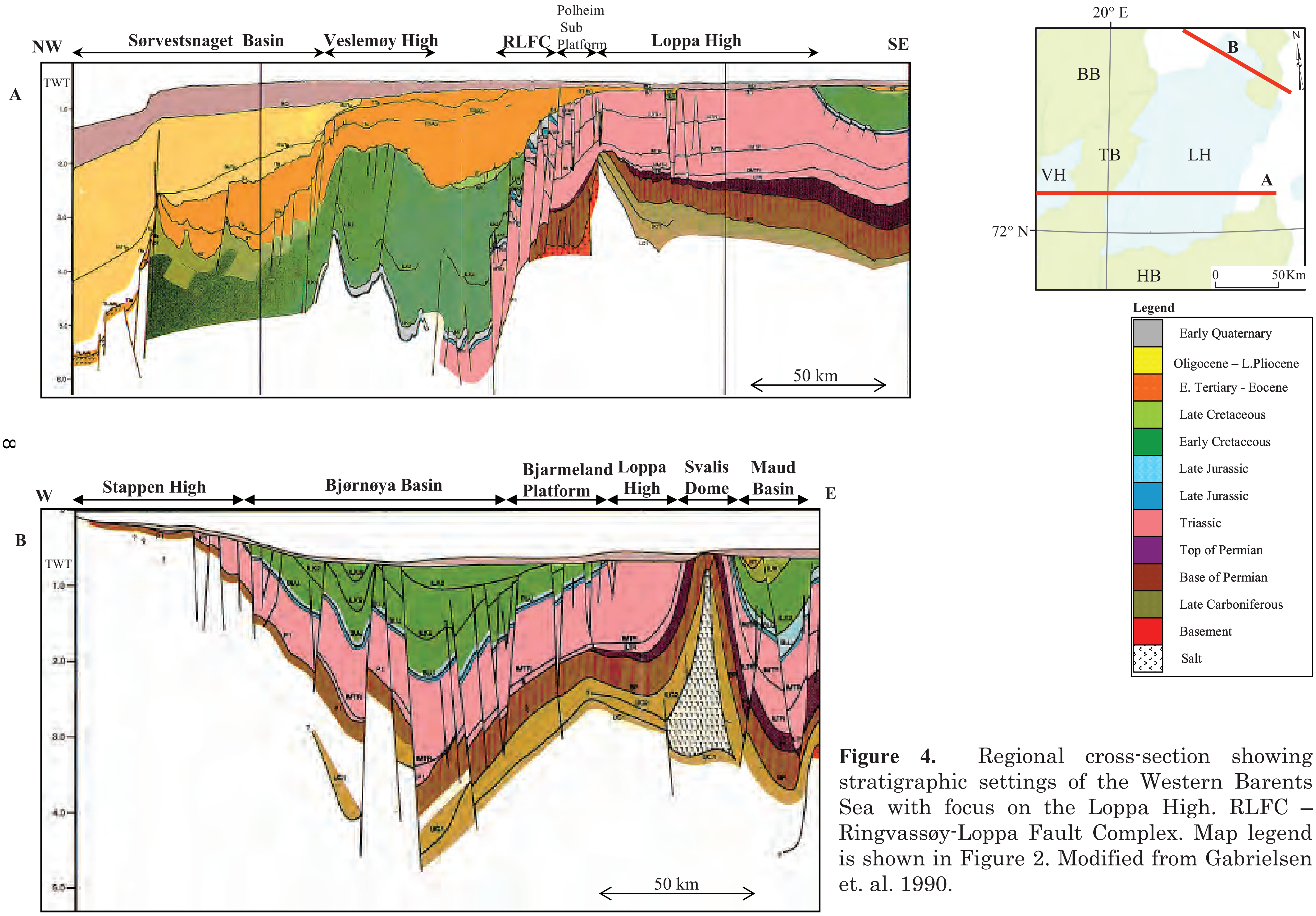
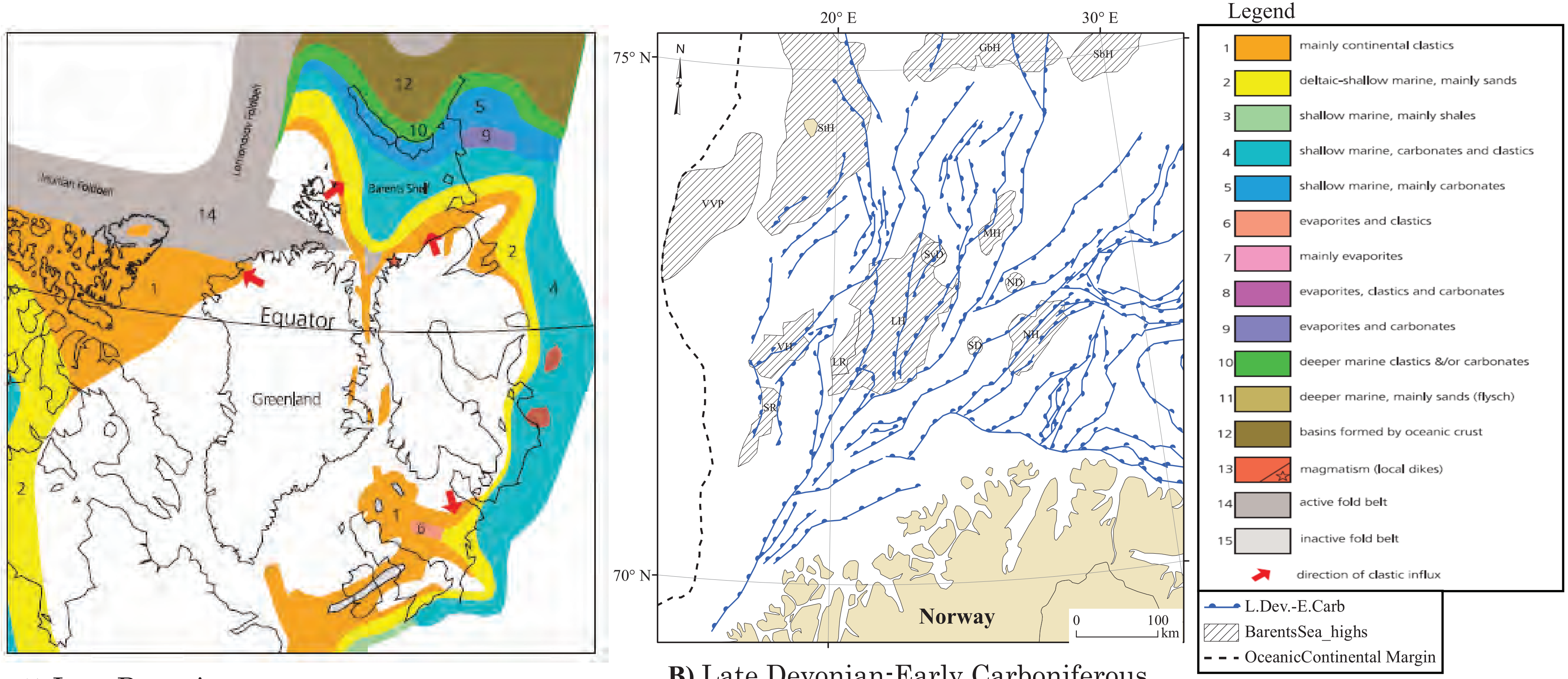


Figure 4. Regional cross-section showing stratigraphic settings of the Western Barents Sea with focus on the Loppa High. RLFC – Ringvassøy-Loppa Fault Complex. Map legend is shown in Figure 2. Modified from Gabrielsen et. al. 1990.



A) Late Devonian

B) Late Devonian-Early Carboniferous rifting phase

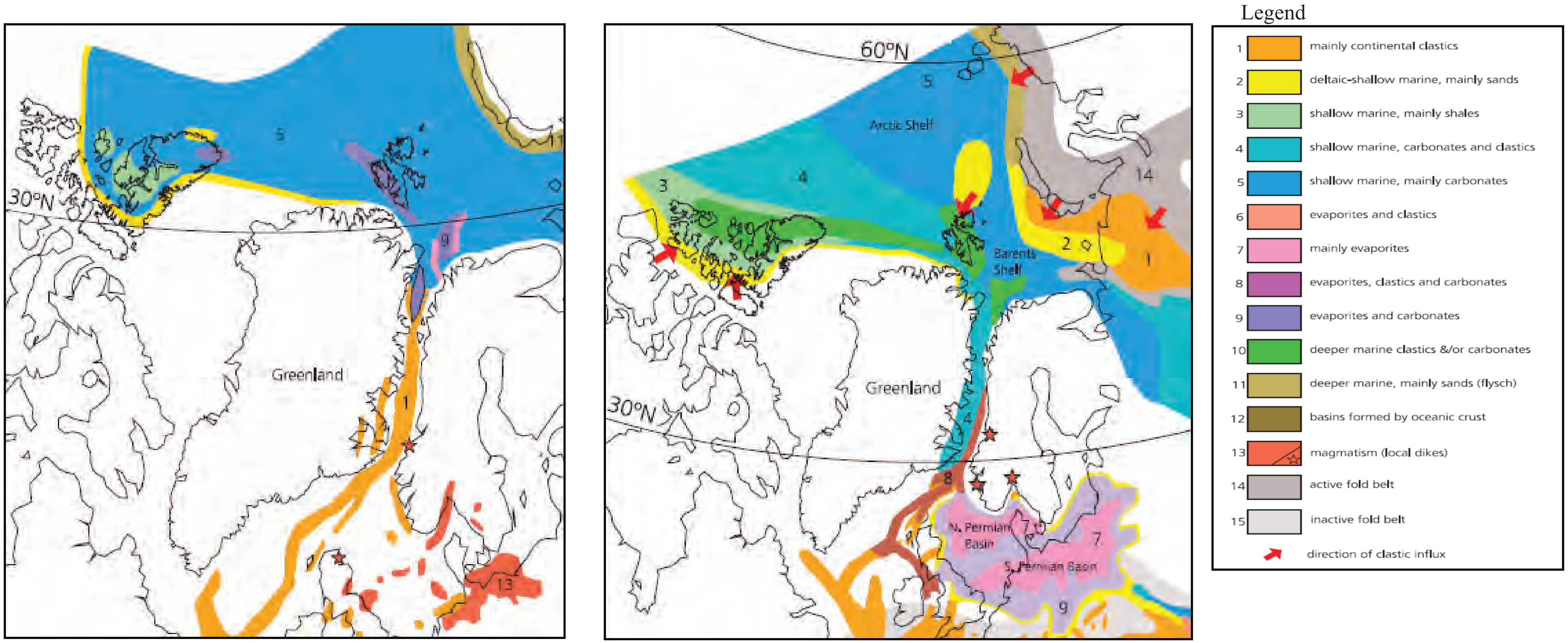
Figure 5. A) Map showing Late Devonian regional palaeogeography.
B) Map showing rifting event in the Western Barents Sea during Late Devonian-Early Carboniferous. Modified from Dengo & Røssland, 1992, Torsvik et. al., 2002.

Middle Carboniferous- Permian: (Figures 5C & 5D)

By the Late Devonian- Early Permian, northward drift of the Laurassia supercontinent carried the Barents Sea into subtropical latitudes (0°-30°N) (Figure 5C). During the Late Permian, the Barents Shelf had drifted out of the subtropics and mid Norway was located at ca. 35° N. Marine transgression, creating deep marine areas, had advanced southward through a developing Norwegian-Greenland rift system, and carbonates and evaporites were deposited due to warm and arid climate (Figure 5D).

By Middle Carboniferous time, fault movements ceased in the eastern areas, and most of the Barents Sea had become a stable platform. Major marine transgression during the Late Carboniferous period transformed the Barents Shelf into a vast, relatively shallow, marine epicontinental basin. At the same time, a carbonate platform of regional extent was developed and covered rotated Early Carboniferous blocks (Wood et al., 1989) (Figure 5C).

Renewed block faulting was active in the Loppa High and Stappen High in the Late Carboniferous to Early Permian (Gabrielsen et al., 1990). An easterly tilting of the Loppa High and Hammerfest Basin in the Late Carboniferous to Early Permian times was caused by an E-W tensional system with reactivation of underlying basement fault trends (Gudlaugsson et. al.1998). Following an Early Permian period of erosion, the Loppa High and other positive structural elements in the area were gradually transgressed. In the Late Permian times the western part of the Loppa High was faulted down to the west along the Ringvassøy Loppa Fault Complex, tilted to the east, and eroded (Dengo and Røssland, 1992).



C) Late Carboniferous-Early Permian

D) Late Permian

Figure 5. C) Map showing Late Carboniferous Early Permian regional palaeogeography. **D)** Map showing Late Permian regional palaeogeography. From Torsvik et. al., 2002.

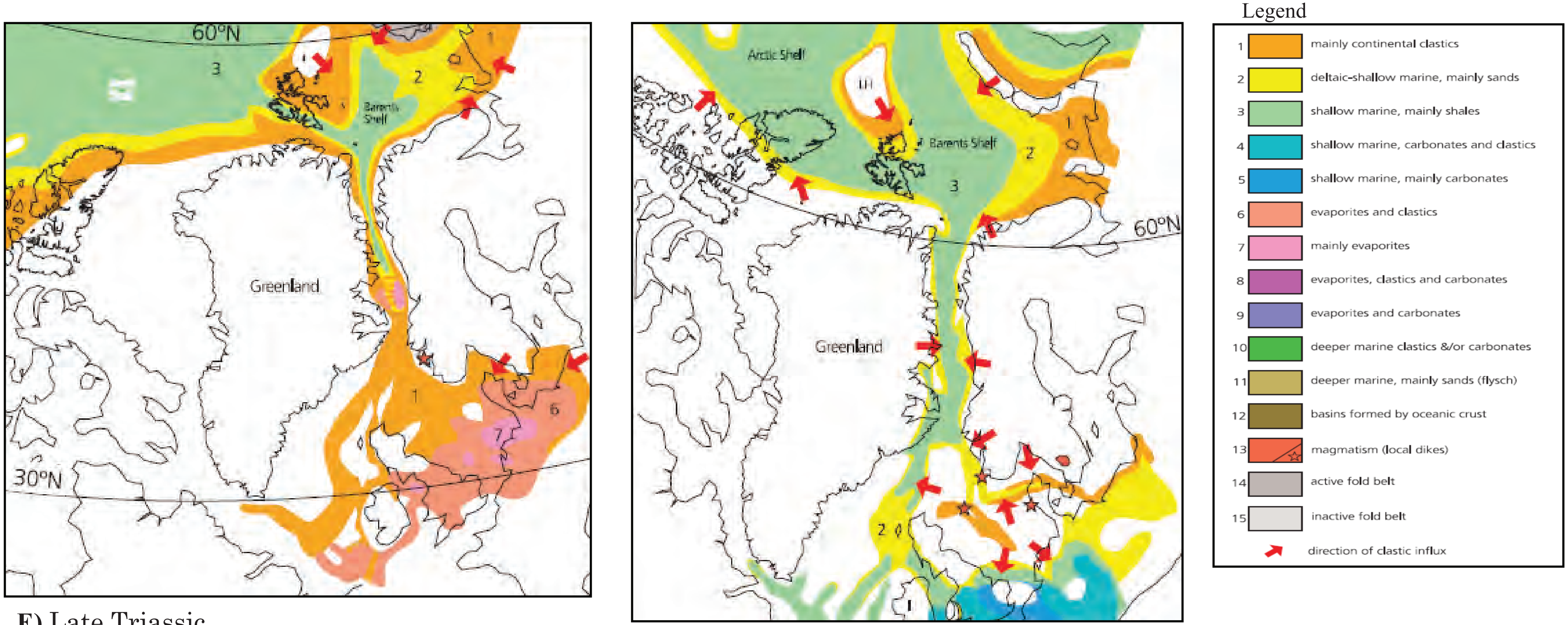
Triassic – Early Jurassic: (Figure 5E)

The Early Triassic was characterized by high rate regional subsidence due to large amount of sediment influx from the east (Gabrielsen et al., 1990, Gudlaugsson et. al., 1998). The thick Triassic rocks comprise coarsening-upwards sequences indicating transgressive-regressive depositional cycles (Mørk et al., 1989). The Triassic was a period of continued tectonic quiescence.

In the frame of the study area, the extensional episode during the Permian-Early Triassic, caused by reactivation of some basement – involved normal faults, contributed the relief of the Loppa High to expand (Wood et. al., 1989, Dengo and Røssland, 1992). The Stappen and Loppa highs experienced tilting, and the latter experienced erosion of the crest (Rønnevik et al., 1982, Gabrielsen et al., 1990, Gudlaugsson et al., 1998). Later, Loppa High was leveled off and was buried under marine sediments during Late Triassic (Riis et al., 1986, Worsley, 2006) (Figure 5E).

Middle Jurassic – Cretaceous: (Figures 5F, 5G & 5H)

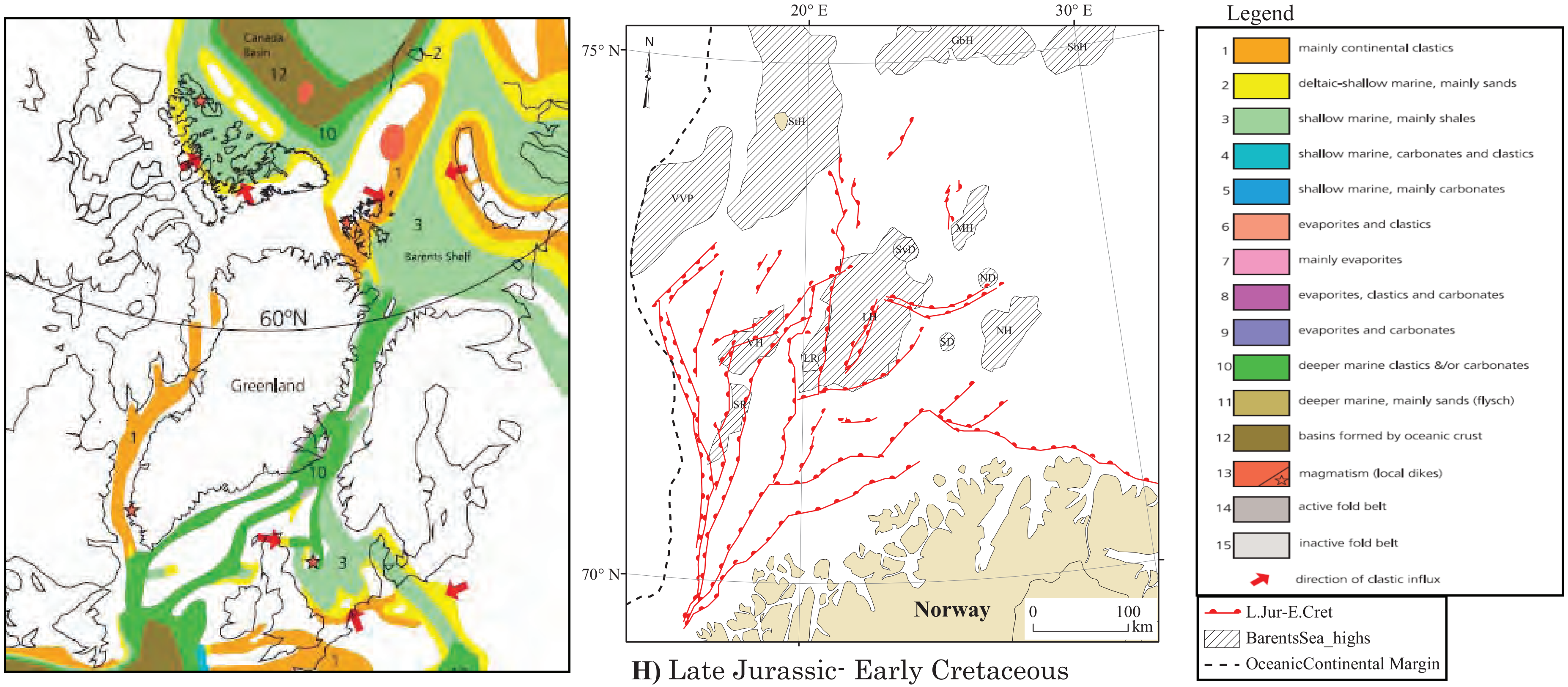
During the early Middle Jurassic, sea level fall caused rapid progradation of deltaic sediments into the Barents Sea (Torsvik et. al., 2002) (Figure 5F). Renewed crustal extension between Greenland and Norway during the Late Jurassic to Early Cretaceous caused a long-term uplift of the Loppa, Stappen, and Sentralbanken Highs (Wood et. al., 1989, Torsvik, et. al., 2002, Nøttvedt and Johannessen, 2008) (Figure 2) (Figure 5G & 5H). This event led to erosion of the Jurassic and Triassic sediments over the highs. During the Early Cretaceous, parts of the Loppa High were eroded, exposing strata as old as Triassic. Deep canyons that formed channels for the transport of sediments into the adjacent basins are visible on the seismic data (Wood et. al., 1989, Brekke & Olaussen, 2008). Simultaneously, the structurally low part of the Loppa High was onlapped during the Early Cretaceous. Extreme rates of fault-controlled subsidence are observed in the Tromsø and Bjørnøya Basins during the Early Cretaceous (Hauterivian - Albian) (Gabrielsen et. al., 1990, Dengo and Røssland, 1992). During the Late Cretaceous, the propagation of the Atlantic rift northwards caused global sea-level rise. However, Barents Shelf was uplifted and subjected to erosion, which increased northwards (Torsvik et. al., 2002). Although reactivation of the major faults and extension was more common near the western margin of the Barents Shelf, Tromsø and Bjørnøya Basins experienced a period of passive subsidence during the Late Cretaceous.



E) Late Triassic

F) Middle Jurassic

Figure 5. E) Map showing Late Triassic regional palaeogeography.
F) Map showing Middle Jurassic regional palaeogeography. From Torsvik et. al., 2002.



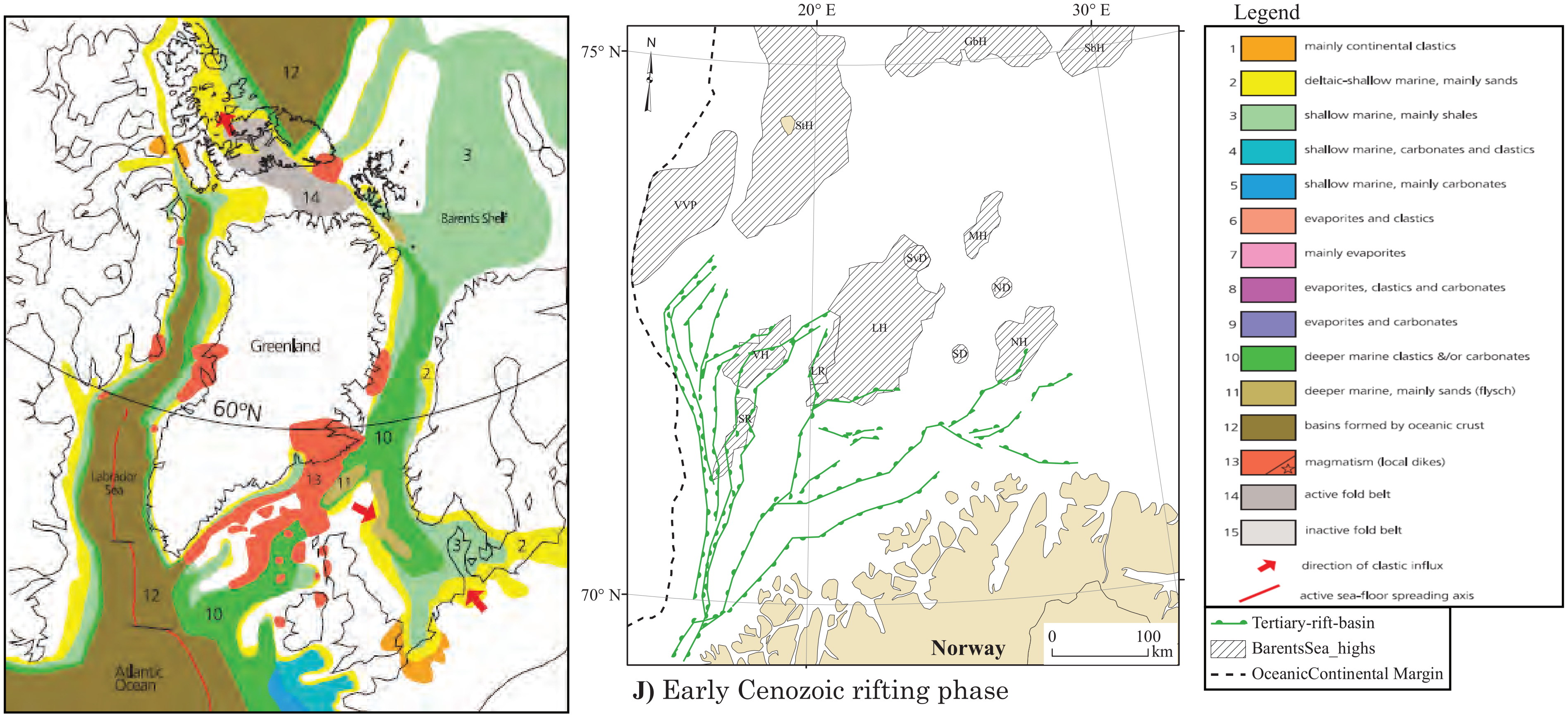
G) Early Cretaceous. Barremian.

H) Late Jurassic- Early Cretaceous rifting phase

Figure 5. G) Map showing Early Cretaceous of Barremian regional palaeogeography. **H)** Map showing rifting event in the Western Barents Sea during Late Jurassic-Early Cretaceous. Modified from Dengo & Røssland, 1992, Torsvik et. al., 2002.

Cenozoic: (Figure 5I & 5J)

Tectonic activity during the Cenozoic is mostly related to progressive northward opening of the North Atlantic and Arctic Oceans since Late Paleocene time (Figure 5I). In the early Cenozoic, the strike-slip movements continued along the same southwestern to northeast trends as in the Early Cretaceous, with deformation concentrating along the main strike-slip zones (Riis et. al., 1986) (Figure 5J). Active basement-involved normal faults are the basin-bounding faults of the Harstad, Tromsø, and Bjørnøya basins. There was deformation related to salt movement and basement-detached normal faulting overlying older basement-involved faults (Dengo and Røssland, 1992). East of the Loppa High, the region was relatively stable. In the Neogene, most of the Barents Shelf was uplifted and eroded (Nøttvedt and Johannessen, 2008). Some possible causes for this uplift are suggested by several workers (Nyland et. al., 1992, Riis and Fjeldskaar, 1992, Clift et. al., 1998, and Praeg et. al., 2005) (Figure 2). Periodic glaciations during the late Pliocene and Pleistocene led to large-scale erosion in the Barents Sea (Vågnes et. al., 1992, Cavanagh, et. al. 2006).



I) Early Cenozoic

J) Early Cenozoic rifting phase

Figure 5. I) Map showing Early Cenozoic regional palaeogeography.
J) Map showing rifting event in the Western Barents Sea during Early Cenozoic. Modified from Dengo & Røssland, 1992, Torsvik et. al.,2002.

DATA AND METHODOLOGY

This study includes a grid of industry regional 2D multi-channel seismic data (MCS) supplemented with 10 exploration wells, from the Norwegian national petroleum database (Petrobank). Some 20 000 km of MCS profiles were selected from a larger database to obtain a regional coverage of the study area. Figure 6 shows the study area with the selected dataset.

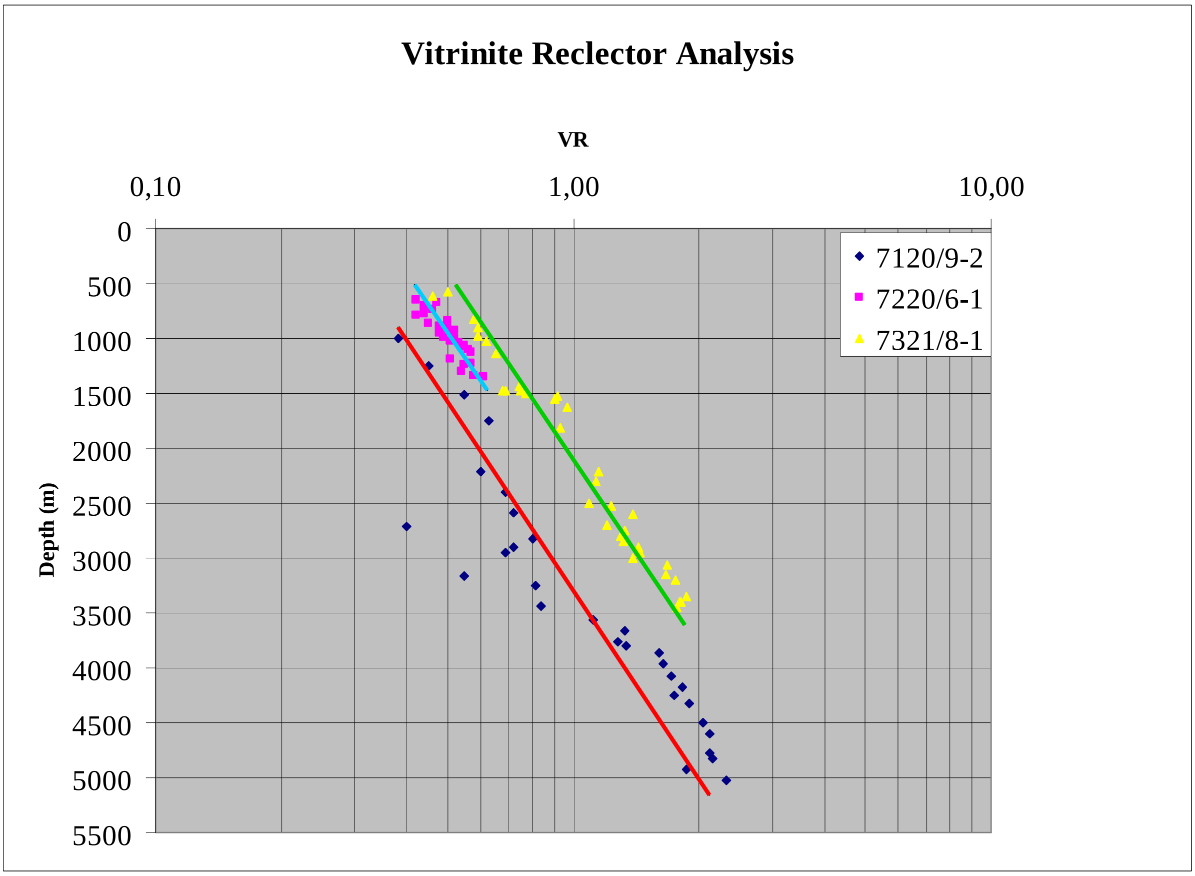
In Appendix A, table 1 lists the name, year of acquisition and extent of the surveys that have been used for seismic interpretation. The quality of the data varies, but, in general, is good. Because of the multiples and gas chimneys, however, there are some areas where the quality of the data is poor, such as the eastern parts of the Tromsø and Bjørnøya Basin.

Well data from released exploration wells in the area and close to 2D-lines have been used for reference under the seismic interpretation. In Appendix B, table 2 summarizes the name of the well, its drilling operator name, total depth, and date of drilling, whereas Table 3 (Appendix C) displays the well tops that have been identified by Norwegian Petroleum Directorate (NPD) and published on their web site (www.npd.no).

A suite of logs (gamma ray, sonic, density, and caliper) together with synthetic seismogram was used to determine geophysical properties of the reflector and to correlate the logs with the seismic character (Figure 8).

Conventional interpretation of 2-D seismic data was carried out using Landmark’s OpenWorks™ interpretation software package. Regionally continuous seismic reflections were picked as chronostratigraphically significant surfaces for this study. Time structure maps of significant seismic surfaces and isopach maps of seismic sequences were developed to highlight structural and depositional trends. Landmark ZMAPPlus™ software was used for map creation.

To quantify the amount of the erosion, an estimate based on the seismic data and vitrinite reflectance analysis has been used to quantify approximate sediments columns that were eroded over the study area. The vitrinite reflectance method is widely used as an organic maturity indicator and control parameter for the palaeo temperature in basin modeling. In this study, geochemical data (vitrinite reflectance (VR) and Tmax) is used from three deep wells located in Hammerfest Basin, on the Loppa High and in Bjørnøya Basin. Data are taken from the geochemical well report publish by Norwegian Petroleum Directorate (NPD) (www.npd.no). This data gives the indication on the temperature the sediments have been exposed to, and consequently give the information about the burial history and maturation on the locations in Hammerfest Basin, Loppa High, and Bjørnøya Basin. Before using the vitrinite data, one has to make a critical analysis of the data to determine the most reasonable values of the vitrinite. It is crucial to use the correct values of the vitrinite reflectance in order to get reasonable results. Vitrinite reflectance values are plotted against the well depth to generate the plot.



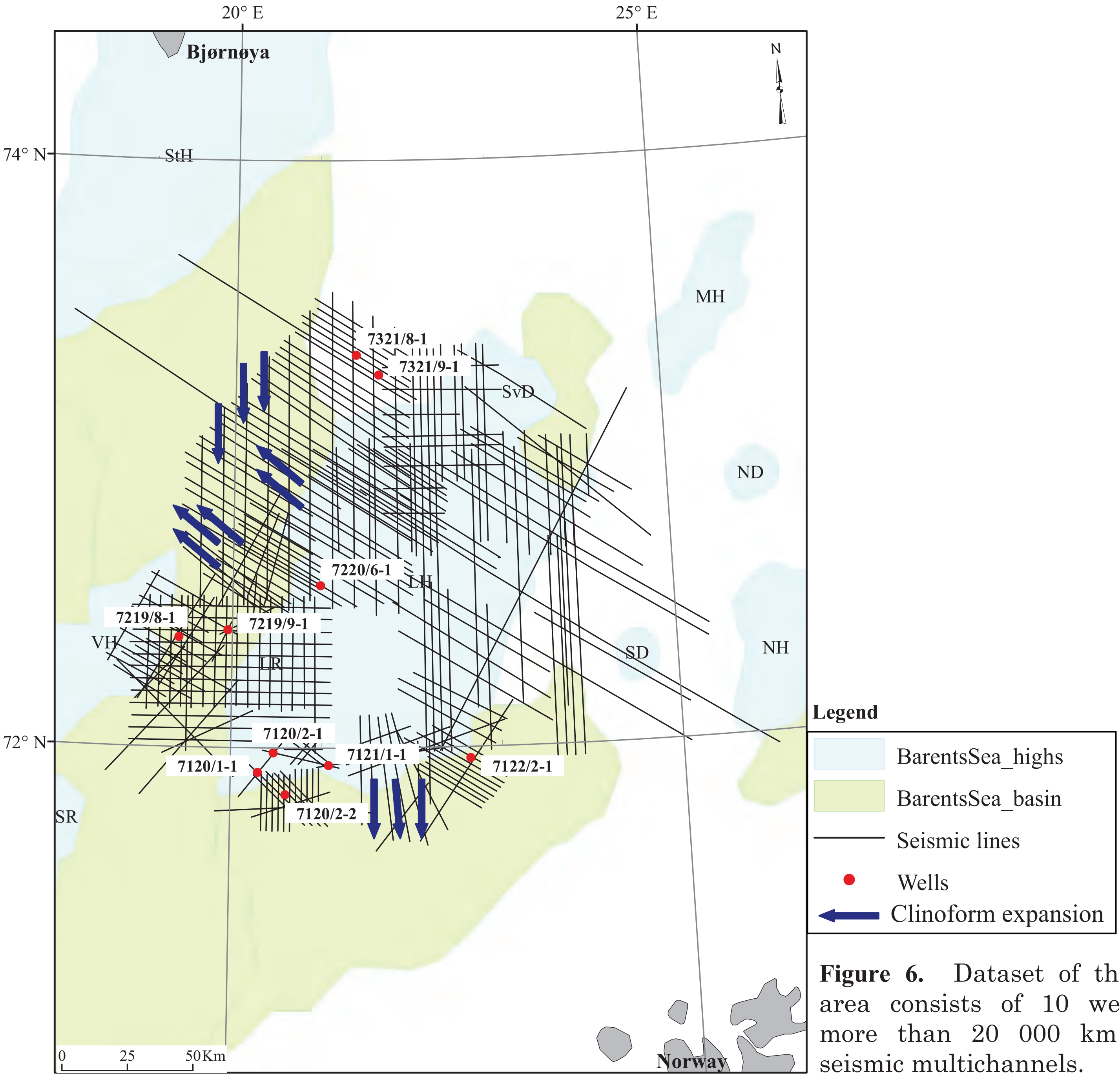


Figure 6. Dataset of the study area consists of 10 wells and more than 20 000 km of 2D seismic multichannels.

STRATIGRAPHIC AND STRUCTURAL OBSERVATIONS ON THE LOPPA HIGH

Stratigraphic Framework

Four main sequences are identified based on major unconformity surfaces and onlap/downlap/truncation relationships on the Loppa High and its adjacent basins. The interpretation of sequences was correlated with available well logs and well tops (Figure 7 & 8). In addition, two horizons, the Base Triassic reflector and the erosional surface reflector, have been identified and interpreted and serve as guiding horizons. Type log for the well 7122/2-1 was contacted in order to show the location of the main reflector that defines the sequence boundaries (Figure 9). Due to stratigraphic and structural distinctive characters of individual sequences that influence southeastern, southwestern, and northwestern flank of the Loppa High, it has been decided to divide the Loppa High and adjacent basins into the corresponding areas for descriptive purposes (Figures 10, 11, 12, 13).

Sequence 1 (Base Cretaceous to Barremian)

General description

The sequence 1 is comprised by clastic Lower Cretaceous units. In the seismic interpretation (Figure 10), the base of the sequence is referred to by the Late Jurassic unconformity, the Fuglen Formation, the top of which is dated as Oxfordian age (Table C). However, it is common to mark Late Jurassic unconformity as Middle Jurassic unconformity because of the Late Jurassic group, which is so thin that it is generally impossible to resolve it on the seismic data. Moreover, it is more accurate to define Base Cretaceous unconformity as base of the sequence 1. In this study, Middle Jurassic unconformity is used from now on and used as a reference reflector for the sequence border determination. We focus on the Middle Jurassic unconformity because it is easier to interpret the base of the sequence regionally. The Intra Lower Cretaceous unconformity, the Knurr Formation of Barremian age, represents the top of the sequence 1. The isopach map shows the sequence thickness across the study area (Figure 14).

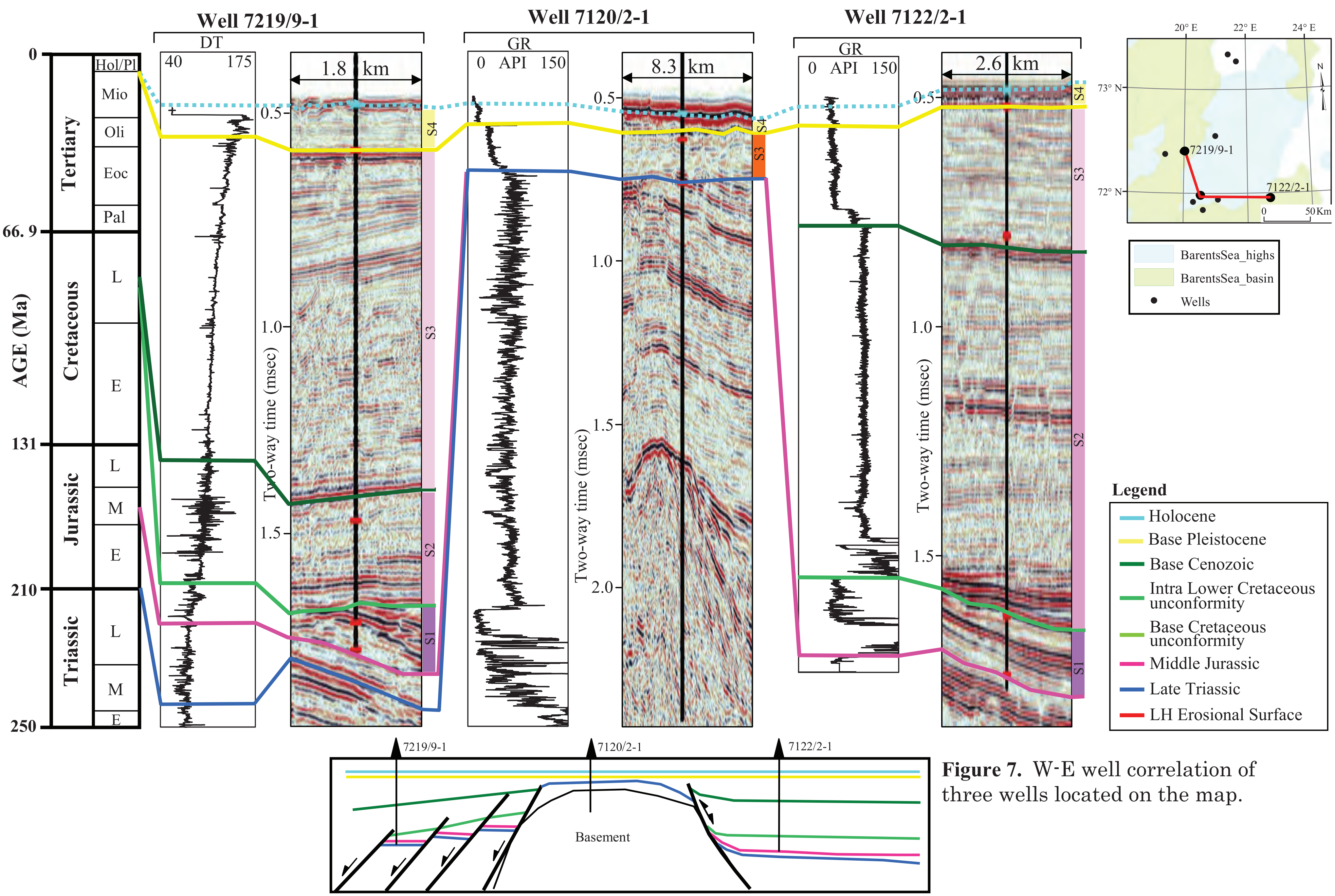


Figure 7. W-E well correlation of three wells located on the map.

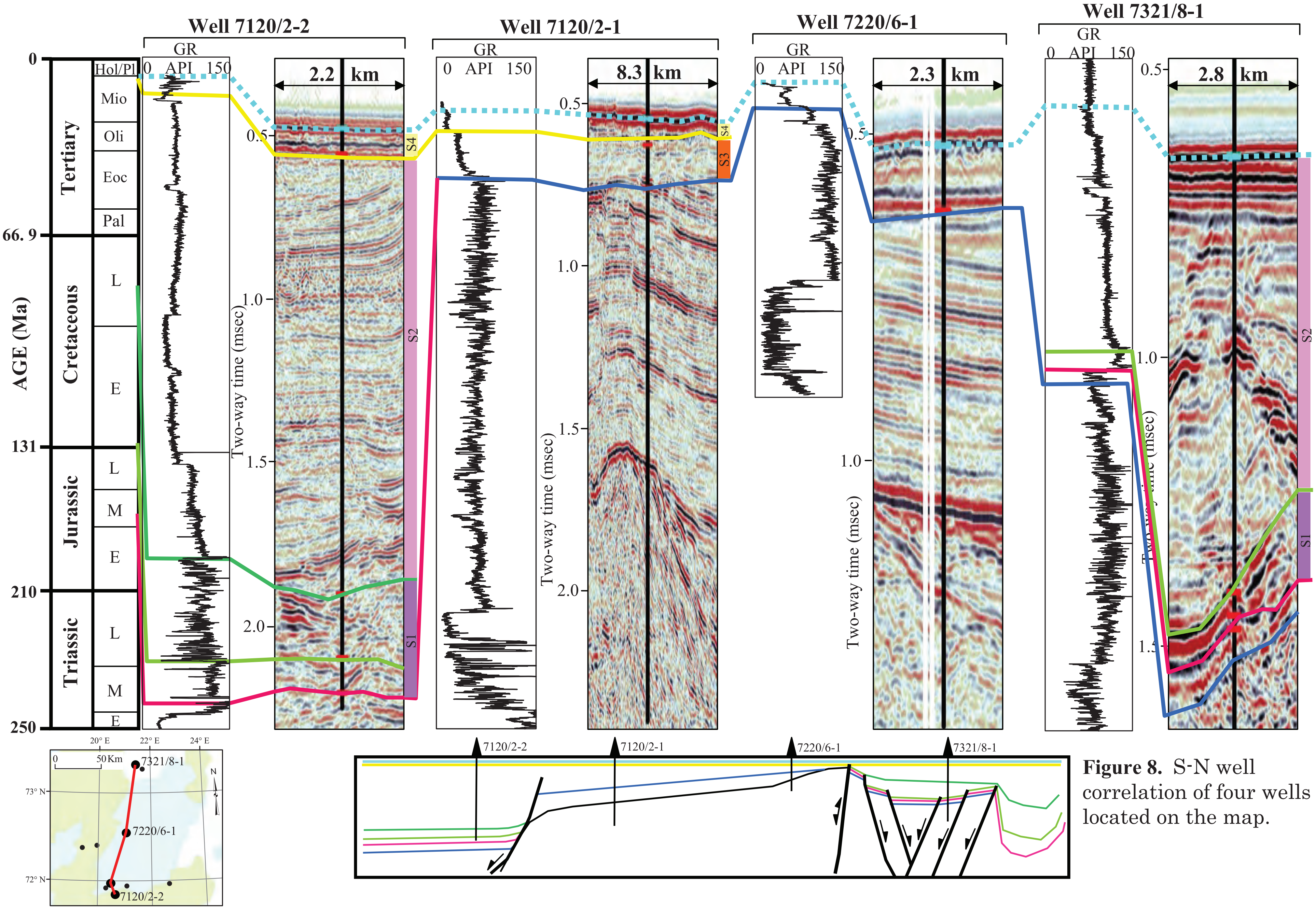


Figure 8. S-N well correlation of four wells located on the map.

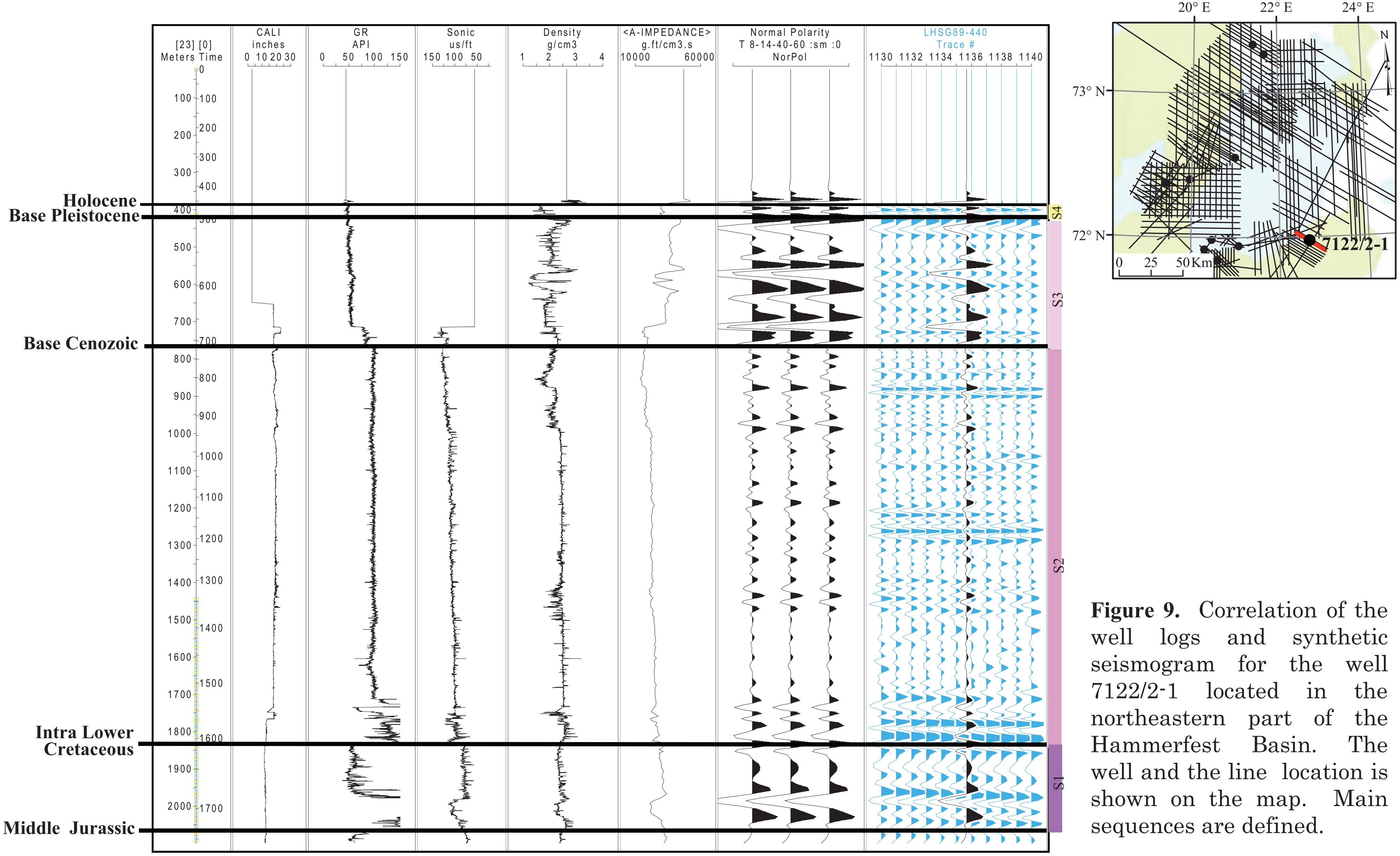


Figure 9. Correlation of the well logs and synthetic seismogram for the well 7122/2-1 located in the northeastern part of the Hammerfest Basin. The well and the line location is shown on the map. Main sequences are defined.

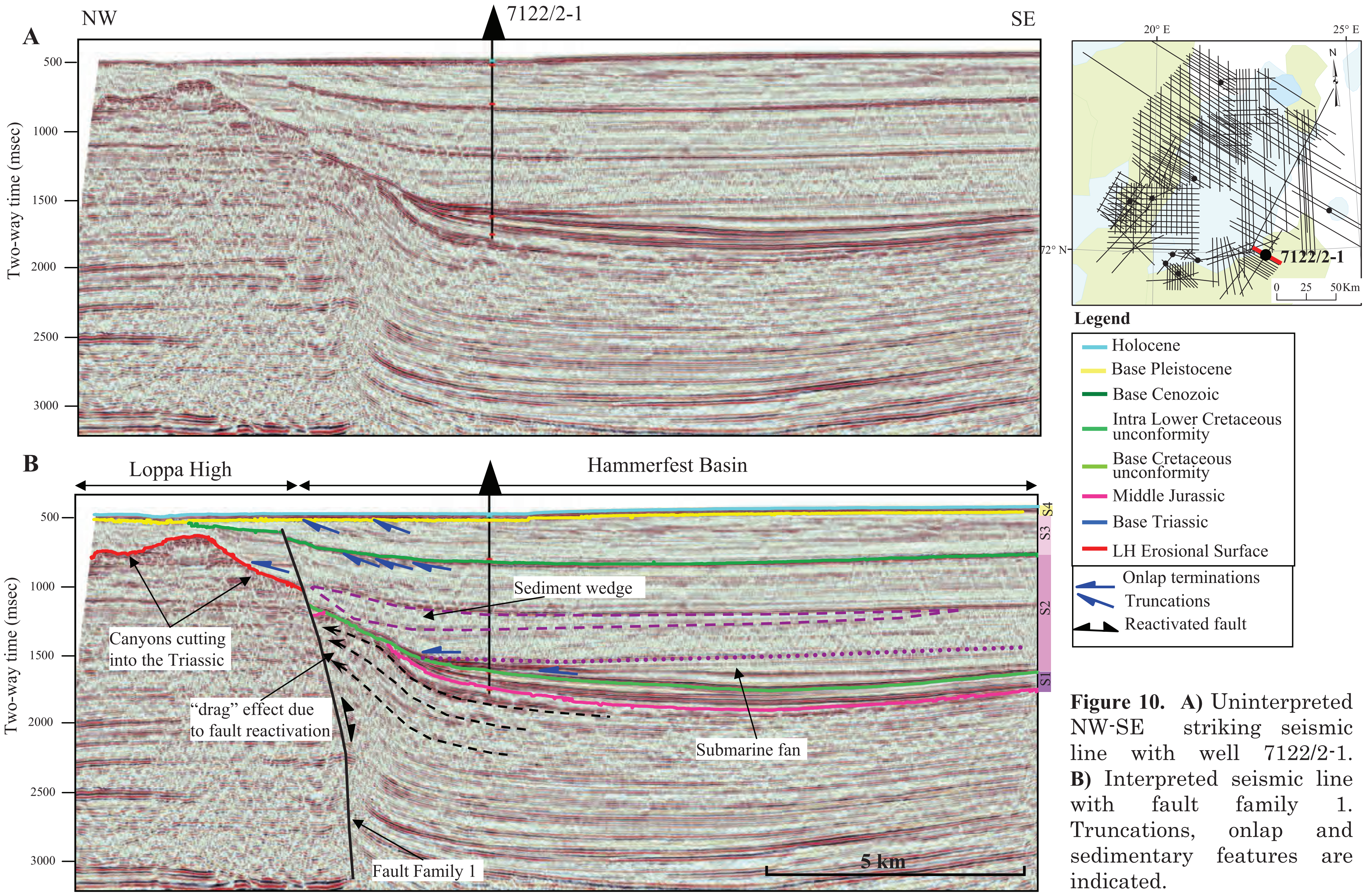


Figure 10. **A)** Uninterpreted NW-SE striking seismic line with well 7122/2-1. **B)** Interpreted seismic line with fault family 1. Truncations, onlap and sedimentary features are indicated.

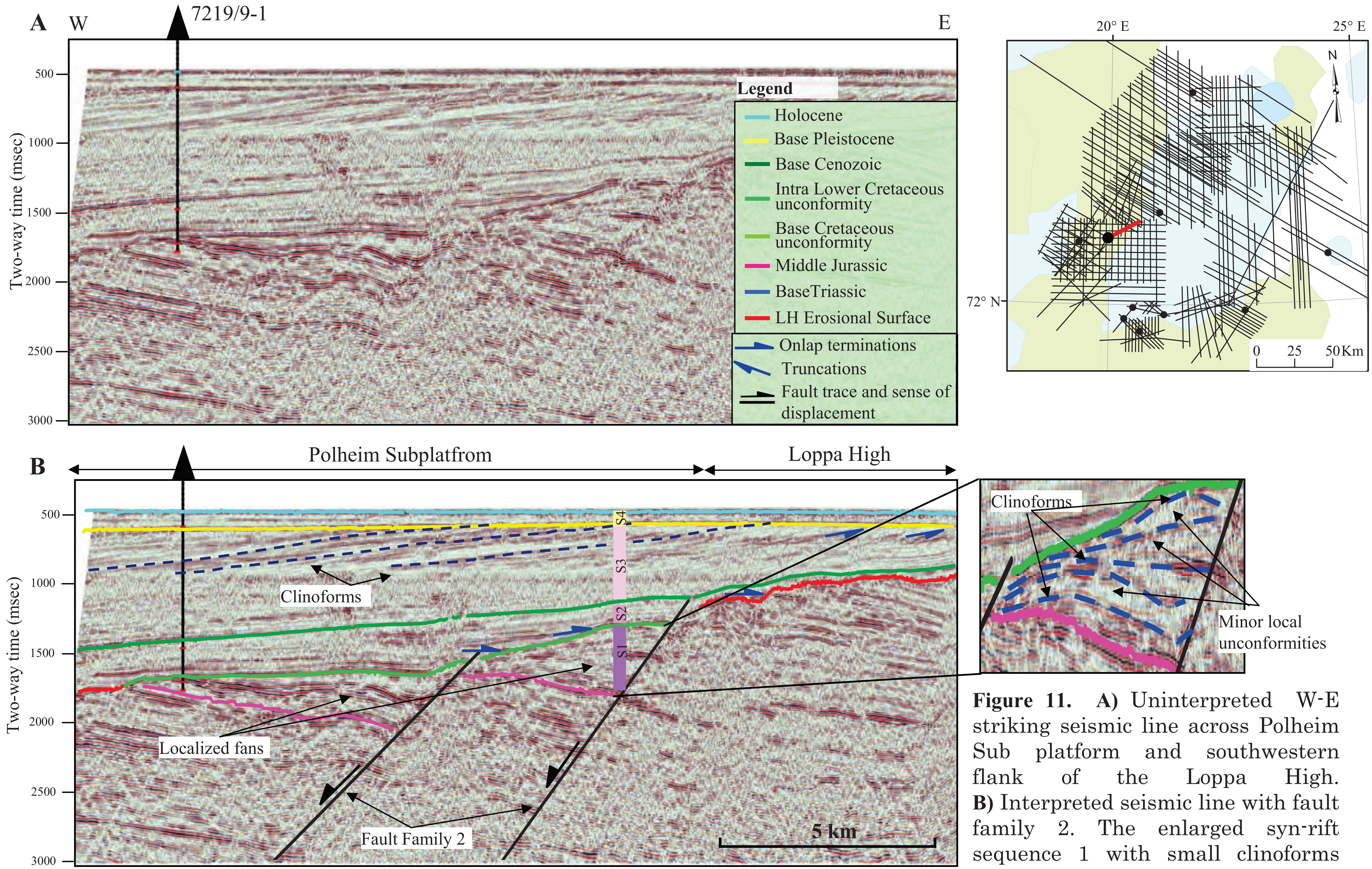


Figure 11. **A)** Uninterpreted W-E striking seismic line across Polheim Sub platform and southwestern flank of the Loppa High. **B)** Interpreted seismic line with fault family 2. The enlarged syn-rift sequence 1 with small clinoforms and minor unconformities is shown in the box above.

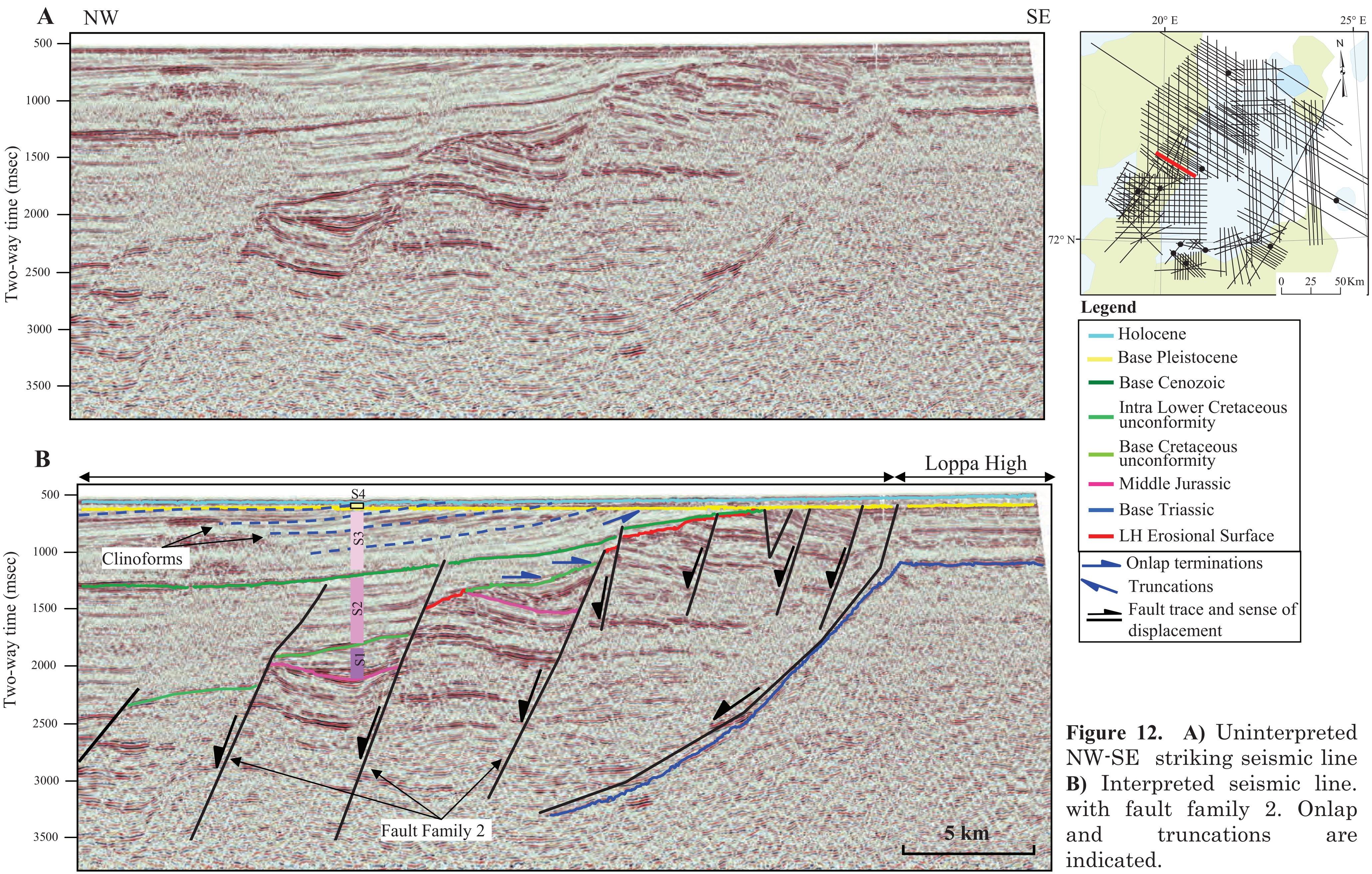


Figure 12. **A)** Uninterpreted NW-SE striking seismic line **B)** Interpreted seismic line. with fault family 2. Onlap and truncations are indicated.

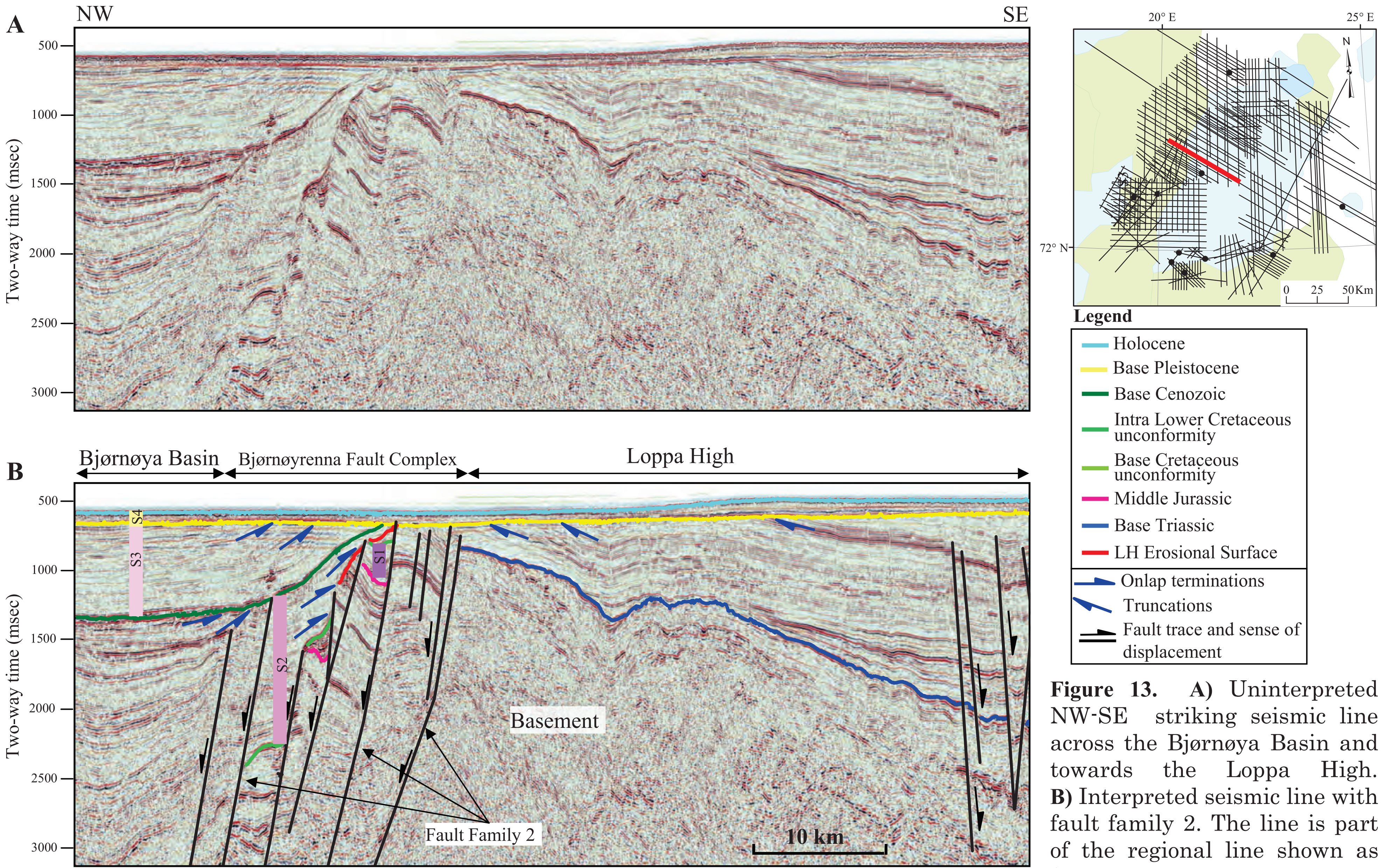


Figure 13. **A)** Uninterpreted NW-SE striking seismic line across the Bjørnøya Basin and towards the Loppa High. **B)** Interpreted seismic line with fault family 2. The line is part of the regional line shown as figure 11.

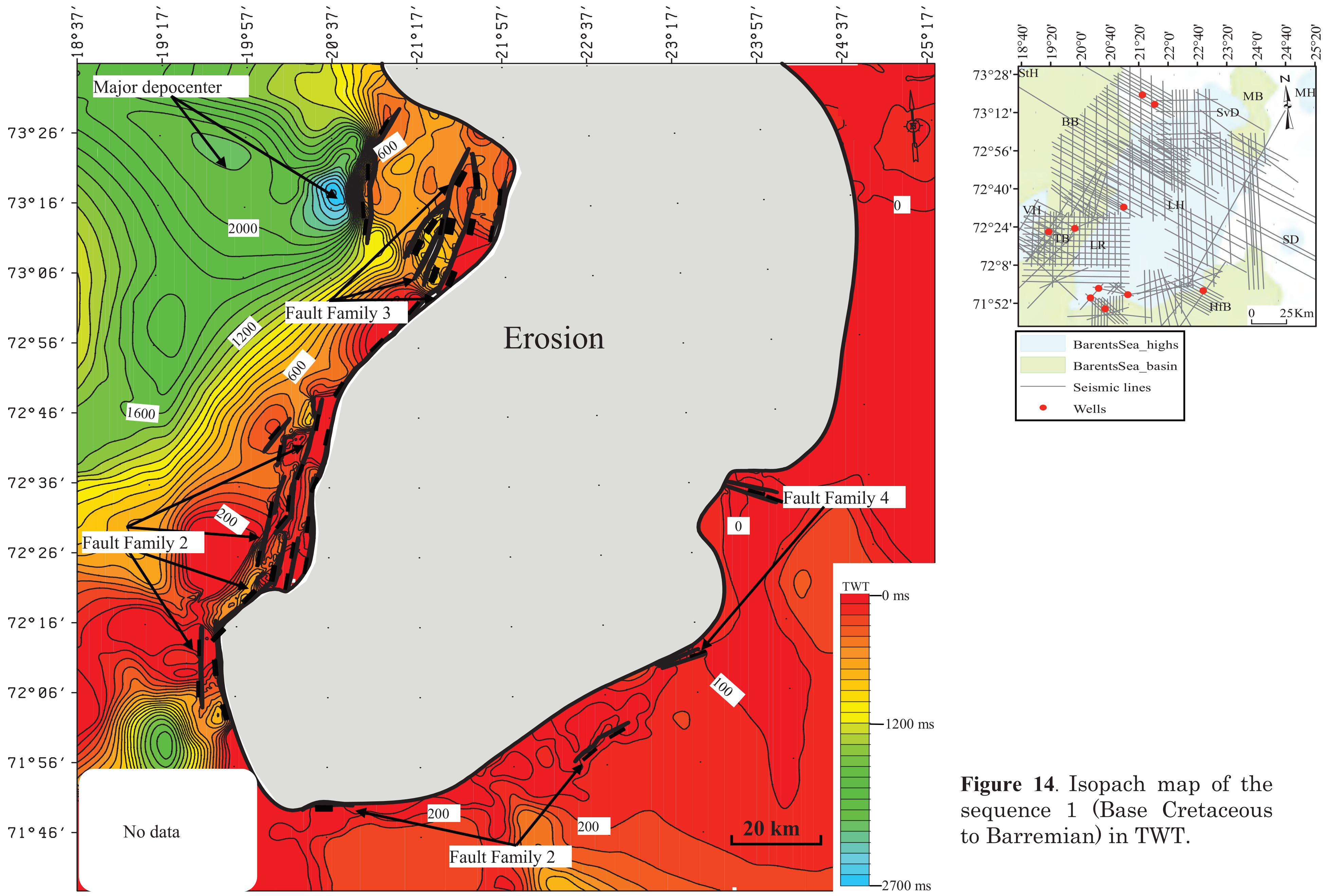


Figure 14. Isopach map of the sequence 1 (Base Cretaceous to Barremian) in TWT.

Well log character

The Middle Jurassic reflector is located at 2025 m depth and has a sharp character on the log profile (Figure 9) due to lithology change from marine shales that characterize the Fuglen Formation and organic rich shales that overlay the formation. Intra Lower Cretaceous reflector is located at 1832 m depth (Figure 9). In the type well, the gamma ray log shows a dramatical break caused by lithology transition from shales and claystones, which belong to Aptian Kolje Formation to massive sandstones of Knurr Formation (Figure 9). The sequence is represented by thick sandstone package shown on the Gamma Ray log (Figure 9). Correlation between the logs and the seismic for both reflectors is good, although it is not exact.

Seismic character and observations

Southeastern part (well 7122/2-1). The sequence consists of well-pronounced, high amplitude, basin-parallel and continuous reflectors (Figure 10). Close to the Loppa High, both Middle and Late Jurassic reflectors have been eroded, whereas Intra Lower Cretaceous reflector demonstrates high – amplitude, continuous reflector, onlapping the Loppa High. The sequence 1 marks the lower part of submarine clastic fan deposited in the marine environment. This sequence unit is characterized by wedging out in onlap against the eroded Loppa High and thickening into the Hammerfest Basin (Figure 10).

South-western part of the Loppa High (well 7219/9-1). The sequence is constituted by some high-amplitude reflectors mixed with low-amplitude markers that have clinoform shape. The sequence rests on wide, extensional blocks (Figure 11). The sediments are deposited in the fault-controlled local depocenters. Further, this sequence shows up to 400 msec growth into the faults with multiple angular unconformities within each extensional block. The small clinoforms are deposited in lobes, what suggests that the sequence 1 is formed as a syn-rift sequence in shallow marine environment (Figure 11 & 12). Here, the well hardly penetrates the sequence 1 due to the rotated position of the fault block.

Northwestern part (well 7321/8-1). The base of the Kolje Formation of Aptian age defines the top of the sequence in this well (Figure 15). The sequence is truncated by the Intra Lower Cretaceous unconformity and gradually thins upwards towards the Loppa High. In contrast, the sequence heavily increases in thickness further down into the Fingerdjupet Subbasin (Figure 15). Another seismic profile reveals that the sequence unit onlaps a tilted high-angle fault blocks in the Bjørnøya Basin and shows a syn-rift deposition before it was downthrown into the basin more than 3 sec TWT (Figure 16).

Northeastern part. Regional transects 15 and 16 exhibit a thin sequence 1 unit that onlaps against the gently tilted eastern side of Loppa High from the east (Bjarmeland Platform). The sequence is truncated by the Base Pleistocene erosional reflector and is eroded on the central part of the Loppa High (Figure 15 & 16).

By summing, the sequence 1 is represented on the southeastern, western, and northeastern flanks of the Loppa High in onlap against the Loppa High. From seismic observations, however, one can recognize important differences in sequence thickness, depositional character, and environment. The sequence is represented by abyssal fan in the southeastern area of the Loppa High and as a syn-rift sequence that rests on the extensional fault blocks along the western flank of the Loppa High. In addition, the top of the sequence 1 can be defined either by the Early Cretaceous unconformity of Barremian age as in the Hammerfest Basin (Figure 10) or by the base o Kolje Formation of Aptian age, as in northwestern part of the Loppa High (Figure 15).

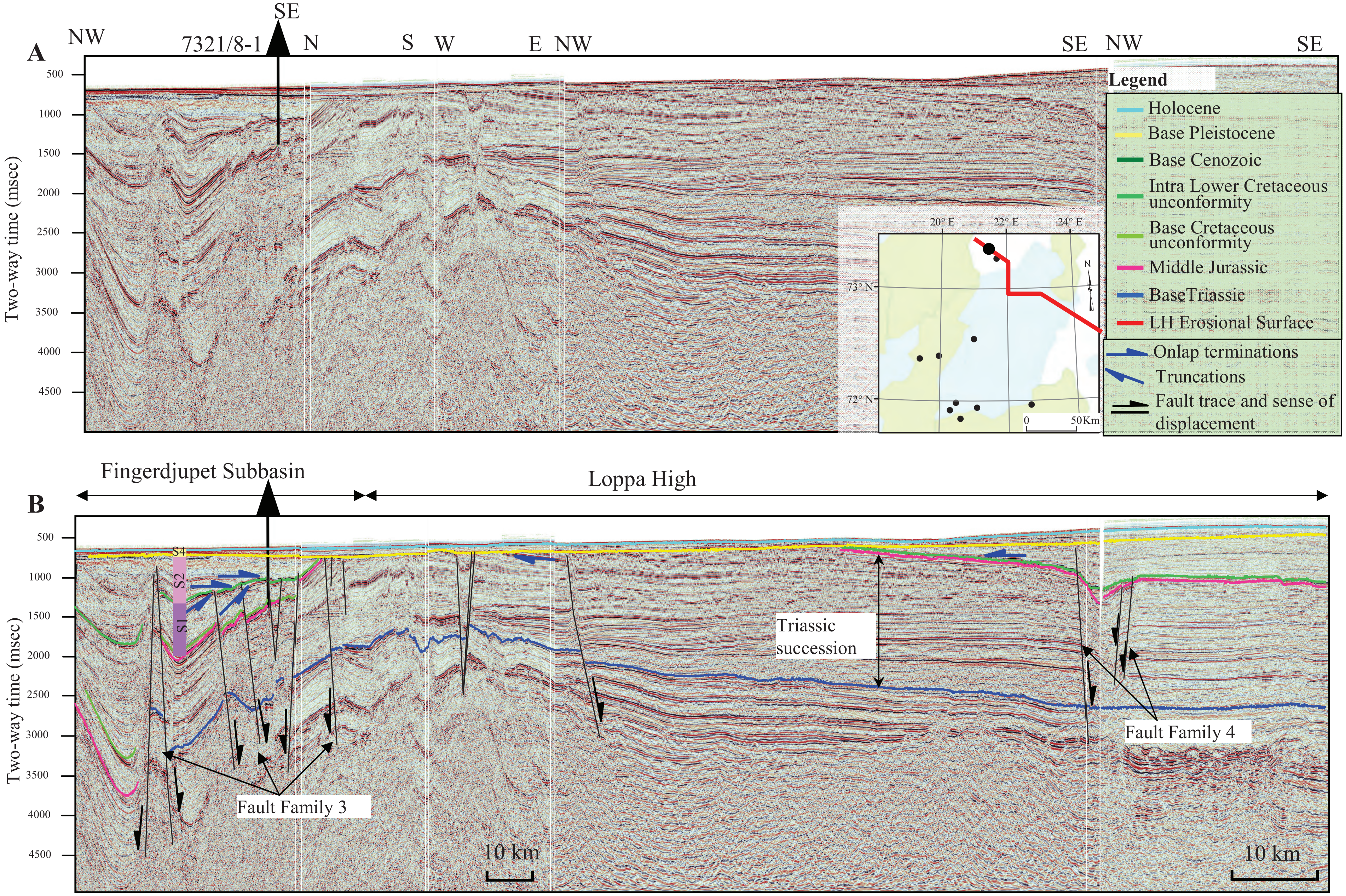


Figure 15. **A)** Uninterpreted NW- SE striking regional seismic line across the Fingerdjupet subbasin and the Loppa High. **B)** Interpreted seismic line with fault family 3 and fault family 4. Onlap/truncation relationship of sequences is indicated.

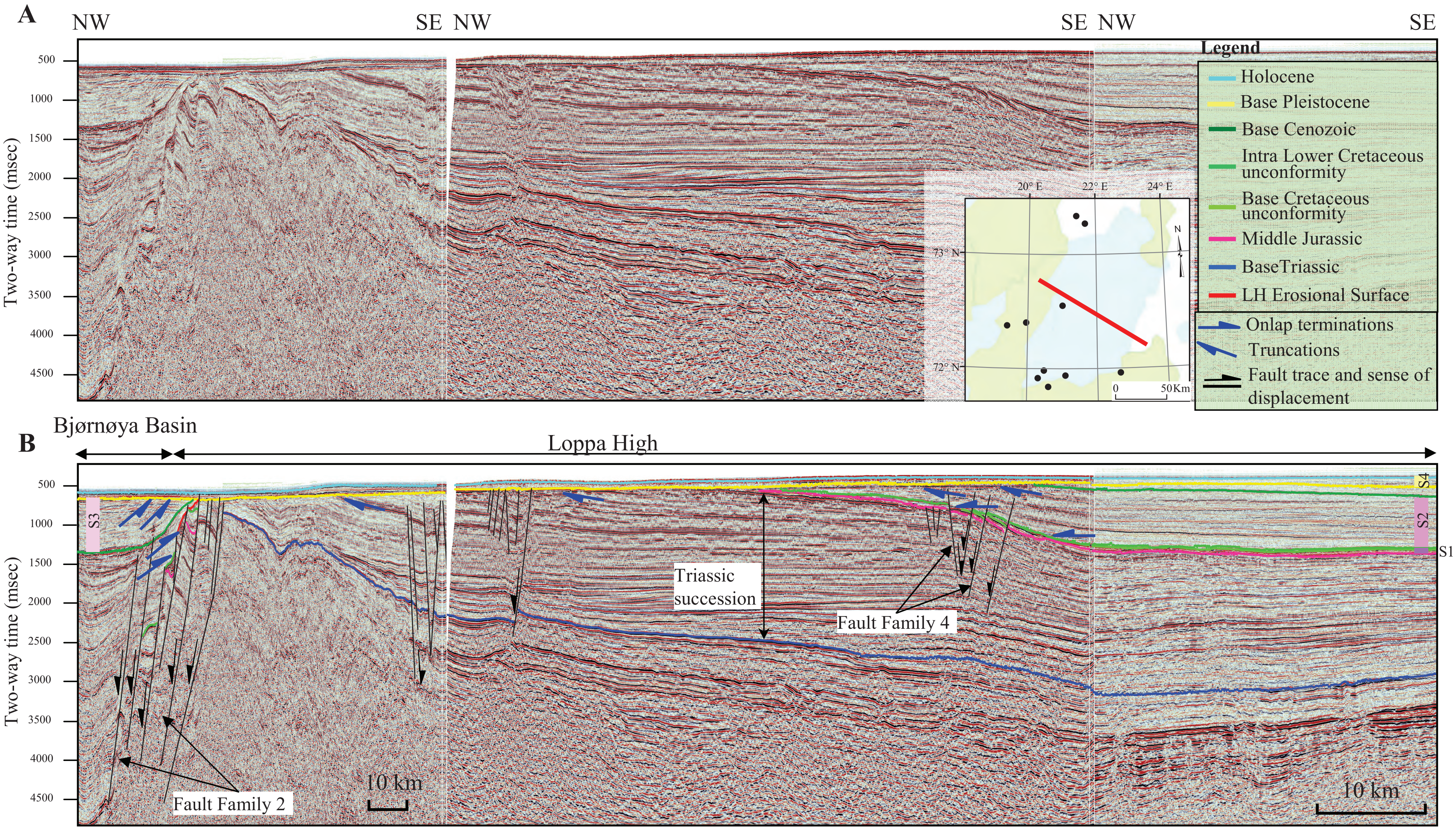


Figure 16. **A)** Uninterpreted NW- SE striking regional seismic line across the Bjørnøya Basin and the Loppa High. **B)** Interpreted seismic line with fault family 2 and fault family 4. Onlap and truncations are indicated on the line.

Sequence 2 (Aptian – Albian)

General description

Sequence 2 is composed of Lower Cretaceous units and rests on the sequence1 with an onlap relationship. The top of the sequence 2 is represented by the hiatus / unconformity surface underlying the Late Cretaceous Strata (Figure 10). Shales and claystones deposited in the open marine environment prevail in sequence 2. The isopach map of sequence 2 illustrates sequence thickness variability across the study area (Figure 17).

Well log character

The Intra Lower Cretaceous reflector that defines the base of this sequence is described in the previous section. The top of the sequence is represented by the Late Cretaceous Strata of the Cenomanian age.

Seismic character and observations

Southeastern part. This sequence comprises two formations of Aptian and Albian age. Thin layers of shales and claystones of the Kolje Formation of Aptian age overlay the submarine fan that defines the sequence 1 and define the base of sequence 2 in the Hammerfest Basin (Figure 10). The Kolmule Formation represents the body of the sequence; basin – parallel, laterally continuous layers of shales and claystones give low-frequency reflectors. To the northwest, the sequence is thinning towards the main fault, slightly wedging. The Loppa High was still uplifted when Aptian - Albian sediments started to onlap onto the high flank. Moreover, wedge development in Lower Cretaceous unit indicates that channels were still active during Aptian - Albian period (Figure 10 & 17). The sequence sediments fill in the canyons that are cut into the Triassic succession. In general, the sequence character in this part of the study area suggests that the sequence was deposited in a tectonically quite period.

Southwestern part. The sequence exhibits variations in thickness by wedging out towards the Loppa High and constant thickening towards the Tromsø Basin (Figure 11 & 12), where the shale succession was registered to be 1200 m thick (Faleide et. al., 1993). The sequence 2 onlaps against western flank of the Loppa High and is eroded on the high itself. The Lower Cretaceous sediments rest on the Triassic succession separated by the erosional surface described below.

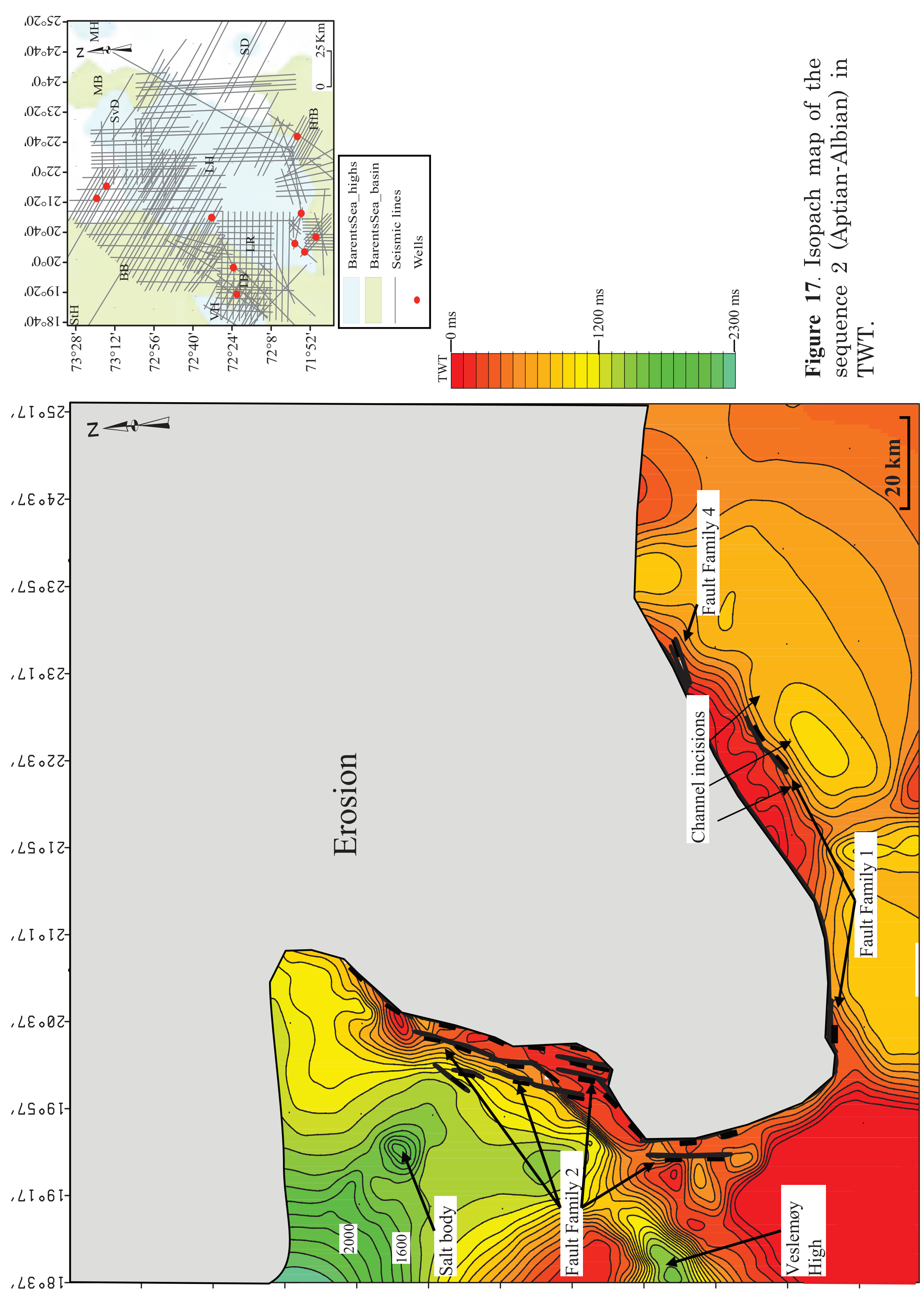


Figure 17. Isopach map of the sequence 2 (Aptian-Albian) in TWT.

Northwestern part. The sequence onlaps against tilted fault blocks of Bjørnøyrenna Fault Complex before it was uplifted and eroded by fault block reactivation. In the Bjørnøya Basin, the sequence thickness increases more than 2 sec reflecting rapid post-rift subsidence in the southwestern Barents Sea (Figure 2 & 13). The Aptian-Albian succession is wedging out in onlap against the western crest of the Loppa High.

Northeastern part. Propagating from the Bjarmeland Platform, parallel, laterally continuous layers of the sequence pinch out on the eastern side of the Loppa High (Figure 16). The sequence unit is tectonically affected by minor grabens and half-grabens, but in much smaller scale than in the rest of the study area (Figure 15 & 16).

In sum, the sequence 2 overlays the sequence 1 in onlap relationship on the southeastern and western flanks of the Loppa High and is not preserved on the Loppa High itself. The sequence is pinching out towards the high where it is eroded by the Base Pleistocene glacial erosion. The sequence is showing the constant thickness towards the Tromsø and Bjørnøya Basins reflecting a rapid subsidence during the Late Cretaceous.

Late Cretaceous Strata

General description

The Late Cretaceous Strata are represented by the upper part of the Kolmule Formation of Cenomanian age at its base and Kviting Formation of Campanian age at its top. The lower boundary of these strata is truncating the upper strata of sequence 2 towards the Loppa High and the upper boundary towards the Paleogene succession is represented by a hiatus in the type well (Figure 10). The strata are not defined as sequence in this study due to lack of the data in the study area.

Although, Late Cretaceous succession is deposited in the southwestern Barents Sea, it is difficult to resolve it in seismic profile east of the Ringvassøy – Loppa High Fault Complex. Therefore, Base Cenozoic erosional boundary is interpreted as the top of this sequence.

Sequence 3 (Paleogene)

General description

The sequence is composed of the claystones – dominated Sotbakken Group (Torsk Formation) and is defined by the Base Cenozoic unconformity at its base. The original top of this sequence is regionally eroded by Base Pleistocene glacial erosion and its depositional character is not known. The sequence unit is dominated by claystones, with minor siltstone, tuffs, and carbonates deposited in the deep marine environments. The isopach map of the sequence shown the thickness variation across the study area (Figure 18)

Well log character

The base of the Torsk Formation is defined by the gamma ray and sonic log responses. However, one has to be critical to log behavior because of the caliper log that shows disturbances in the well (possible casing landing?).

Seismic character and observations

The seismic character of this unit consists of rather parallel continuous reflector in the lower part of the sequence (Figure 7, 8, 12) and clinoforms in the upper part of the sequence (Figure 10, 11 and 13). The sequence 3 is represented in the Hammerfest Basin (Figure 10), Polheim Subplatform, and Bjørnøya Basins (Figure 11, 12 & 13) and is not preserved on the most of the Loppa High due to glacial erosion during the Pleistocene.

Southeastern and southwestern part. In the Hammerfest basin (Figure 10, 11, & 12), the sequence is represented by laterally parallel clinoforms that are truncated by Base Pleistocene reflector. The sequence in Polheim Subplatform is thickening towards the basin, whereas in Hammerfest Basin the sequence unit exhibits rather constant thickness. The upper part of the sequence in the Hammerfest Basin shows slight inclination of the clinoforms towards the Loppa High. Clinoforms observed in these parts of Loppa High are mapped and have a dip in N-S and NW- SE directions (Figure 6) indicating that sediment transport was from Stappen High and Loppa High.

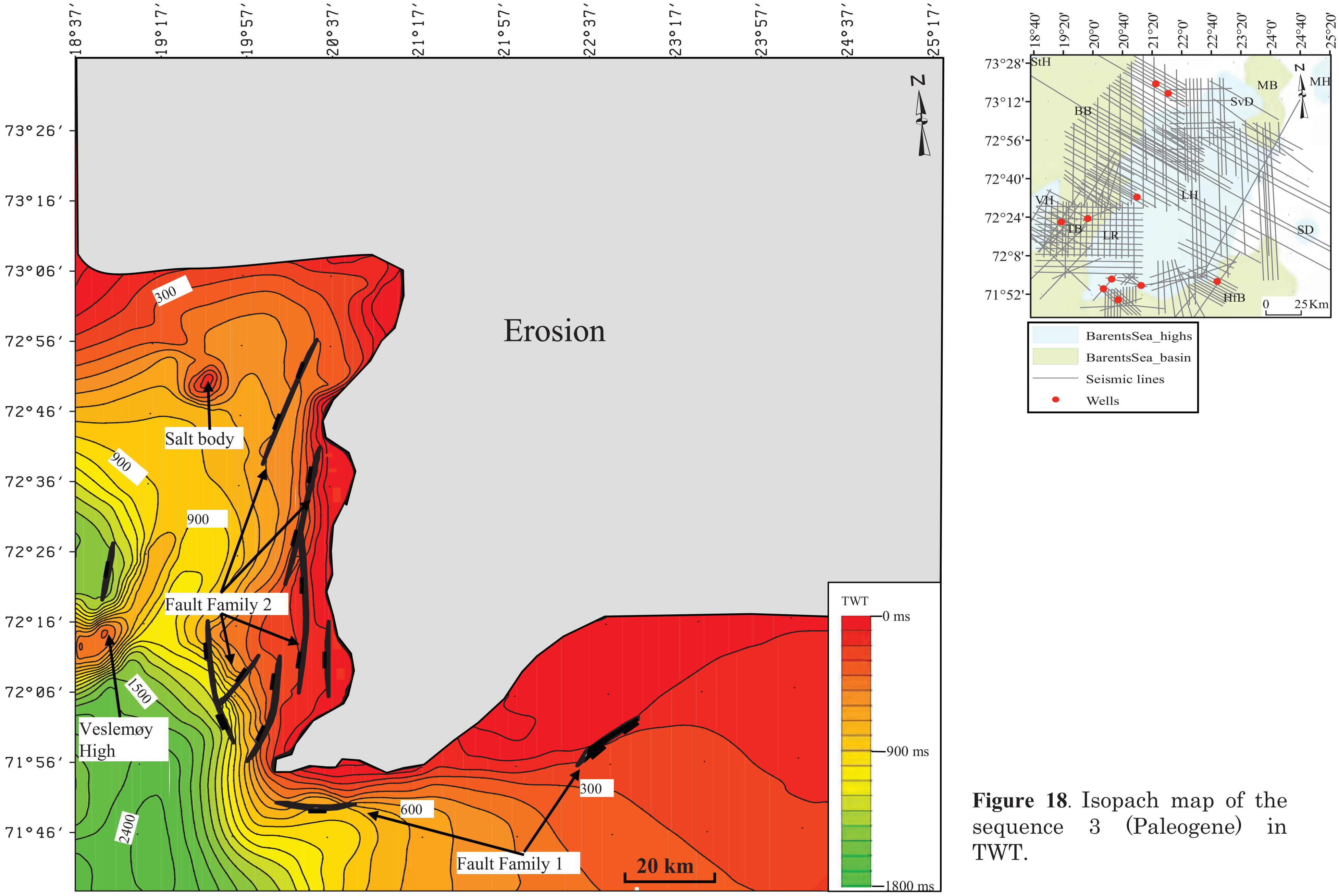


Figure 18. Isopach map of the sequence 3 (Paleogene) in TWT.

Western part. The Paleogene sequence, together with Base Cenozoic reflector, in the western part of the Loppa High is heavily bent upwards (600-700 m) by tectonic event that was younger than all layers that are preserved (Figure 13). From observations, it is clear that sequence 3 was eroded by Base Pleistocene erosional subsurface, after being uplifted.

South part. The Paleogene sequence in the south part of the Loppa High is overlaying the Triassic succession (Figure 7). Uplift of the Barents Shelf, especially the Northern part of it, during the Late Cretaceous can possibly explain the absence of the Paleogene sequence on the central part of the Loppa High.

Sequence 4 (Pleistocene)

General description

The sequence is composed of erosional products that reflect glaciations and periodic uplift during the Pliocene and Pleistocene. The sequence is defined by the Base Pleistocene unconformity as its base and the seabed reflector as its top (Figure 7, 8 & 9). The sequence unit is dominated by glacially reworked sediments that comprise sandstones and claystones with cobbles and boulders of granite, quartzite, and other metamorphic rocks. The sequence is of glacial and post-glacial origin.

Well log character

The boundaries of the sequence have a clear, continuous character that makes it easy to interpret on the seismic data. The sequence shows high amplitude, continuous and rather parallel reflectors (Figure 7, 8 & 9).

Seismic character and observations

The sequence is represented as a laterally continuous unit that occurs over the entire study area with insignificant lithologic variations.

Southeastern and northwestern part. The sequence shows little thickness variation and appears as rather thin unit (50-100 m thick) (Figure 10 & 13).

Southwestern part. This sequence is represented by a rather thicker unit that shows slight thickness increase towards the Tromsø Basin (Figure 11 & 12).

Base Triassic Reflector:

The Base Triassic reflector serves as a guiding reflector and is the only marker that can be traced all over the Loppa High area. As a rule, the reflector has high amplitude and continuous, well-pronounced character that can be easily recognized, especially on the western flank of the Loppa High. The reflector is parallel to Triassic succession and marks the semi - horizontal subsurface that eroded into the basement during the Late Permian/Early Triassic times (Figure 12 & 13). This horizon was interpreted in order to map the semi-horizontal subsurface that covered the top of the Loppa High before it was covered by Mesozoic sediments (Figure 19).

Erosional Surface Reflector:

The given reflector is assigned to an erosional surface that dominates the central part of the Loppa High (Figure 10, 11, 12). The reflector is of uncertain age and is to be assigned in this study. In general, the reflector is interpreted as the top of the Triassic succession of the high (Figure 20).

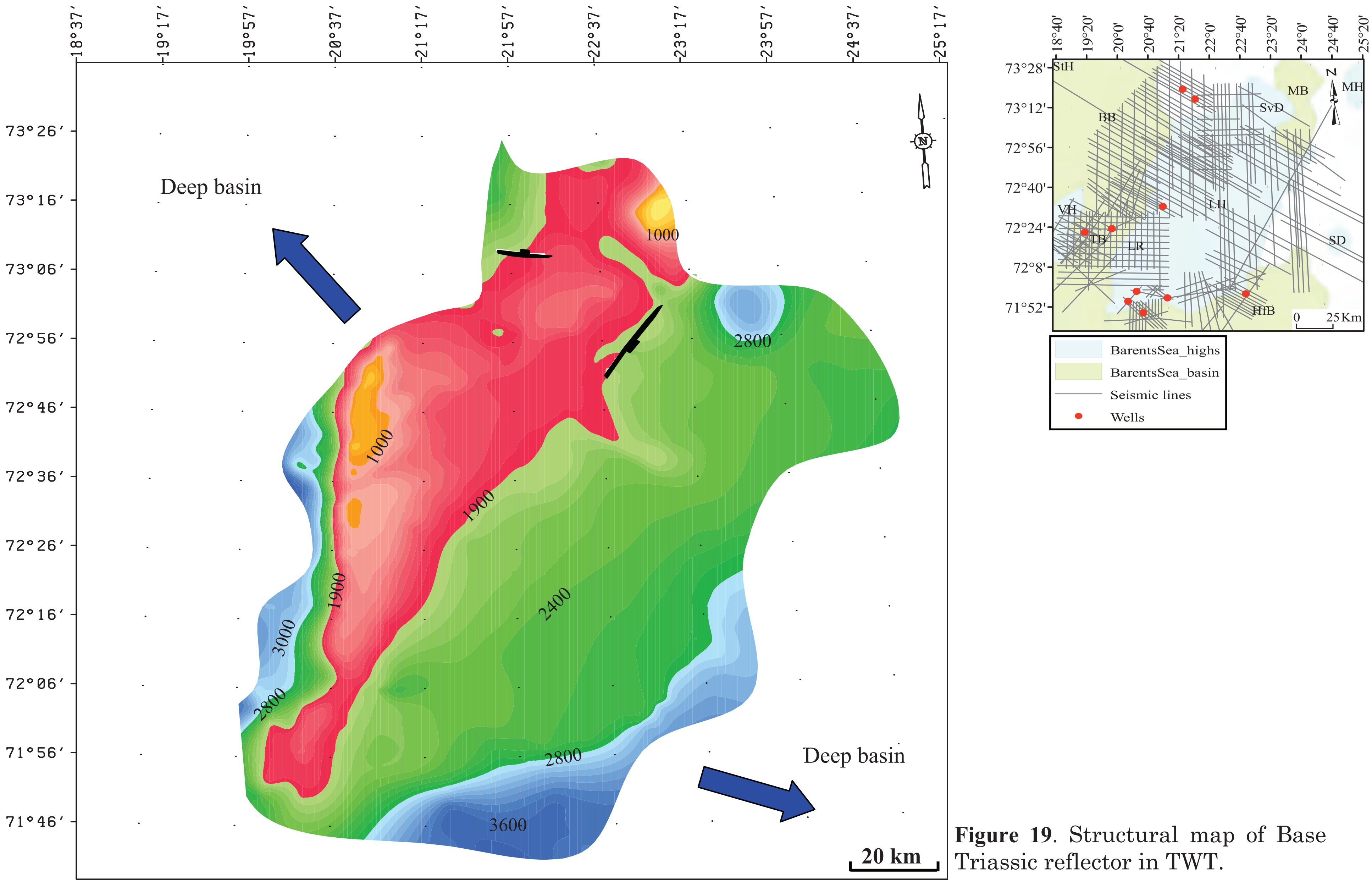


Figure 19. Structural map of Base Triassic reflector in TWT.

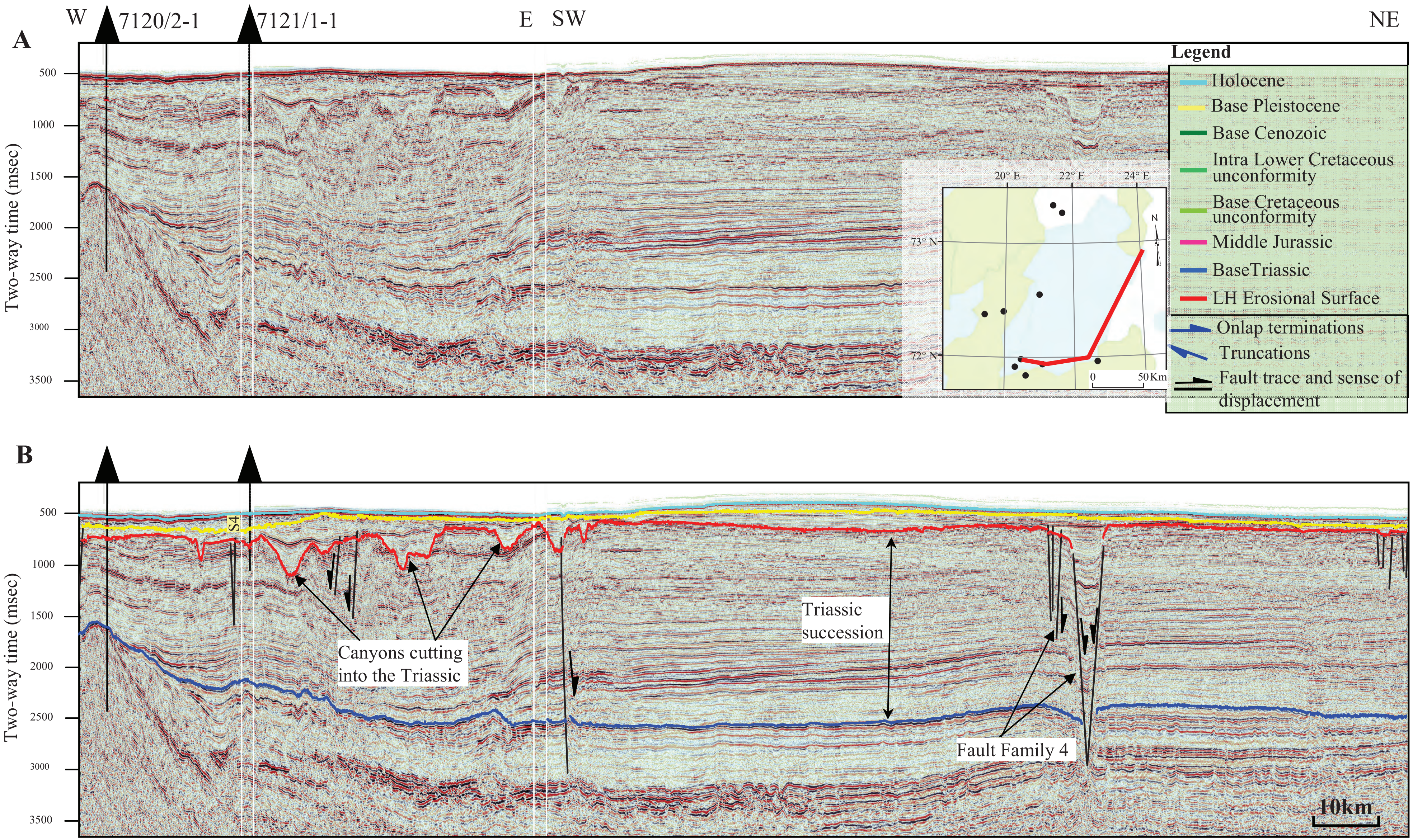


Figure 20. **A)** Uninterpreted W-S and SW – NE striking regional seismic line across the Loppa High. **B)** Interpreted seismic line with deep canyons the Triassic sequence and fault family 4.

Structural Framework

The seismic interpretation reveals several fault complexes affecting stratigraphic sequences. Based on the orientation and the dip angle of the faults, four main fault families have been identified (Figure 21, 22, 23).

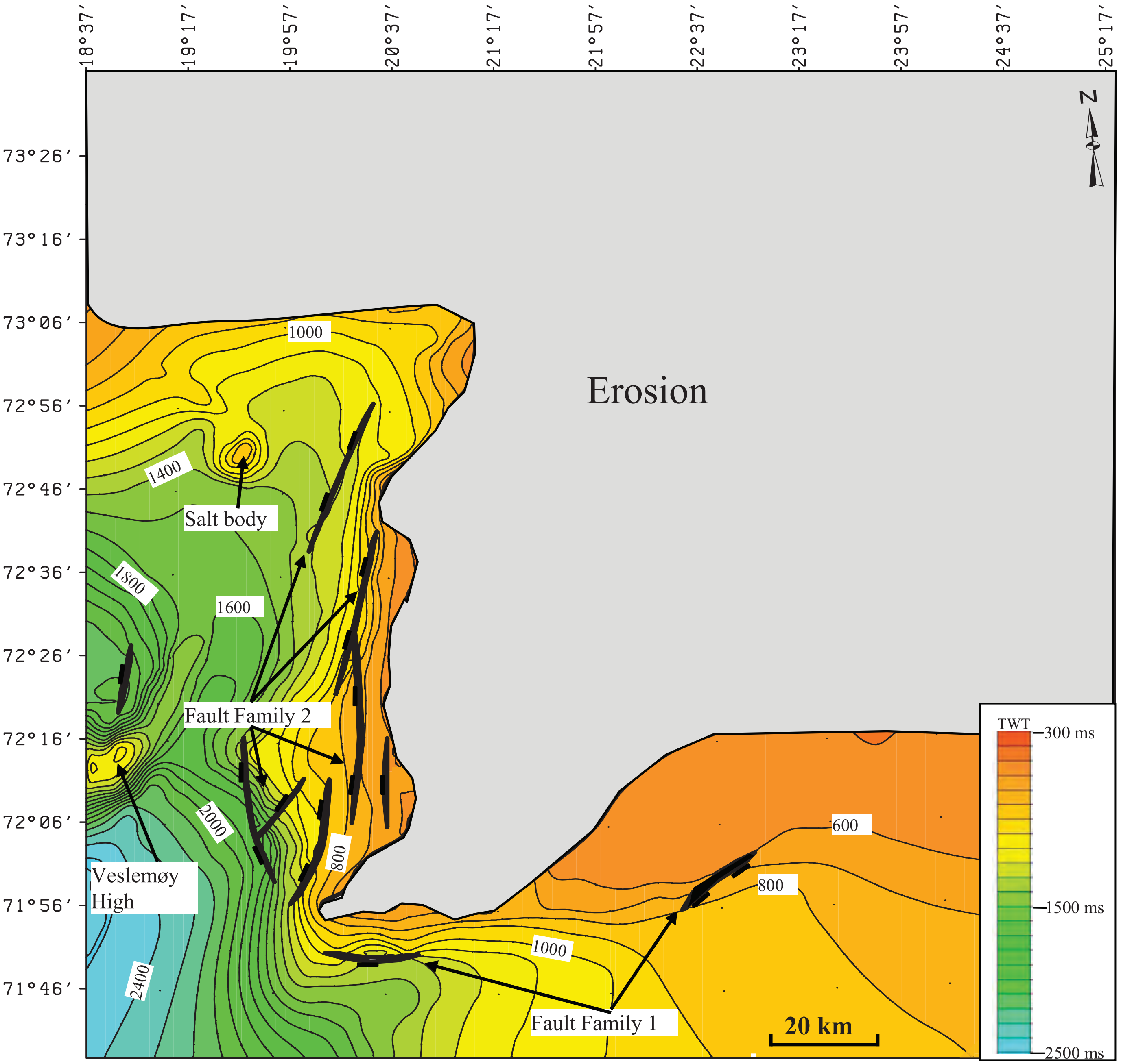
Fault Family 1

This fault family includes normal faults that are part of the Asterias Fault Complex. Faults are located on the south and southwestern flank of the Loppa High and represent the main structural boundary between the high and the Hammerfest Basin. The faults are ENE-WSW oriented with a south-southwestern dip. Seismic profile shows a deep, high - angle fault with several signs of reactivations (Figure 10).

Fault movement in Early Cretaceous (Barremian) led to uplift of the Loppa High. This fault reactivation can be noticed by several observations. Firstly, fault movement shows a large throw into the Hammerfest Basin with a significant drag of Triassic succession along the fault. In addition, the uppermost layers of Triassic strata are rotated towards the fault plane. Secondly, layers within the Barremian sequence are truncated by the Barremian reflector. Lastly, Aptian – Albian sequence onlaps the uplifted and eroded flank of the Loppa High (Figure 10).

The second reactivation event was established in the Late Cretaceous period when sequence 2 was deformed by the renewed fault activity. Truncations of the Aptian-Albian sequence towards the Loppa High can have two possible reasons. First, the renewed uplift of the Loppa High during the Late Cretaceous. Second, relative sea-level drop caused by Barents Shelf uplift (Figure 2). The fault movement is described by smaller throw that might indicate either the extensional nature of the reactivation or the strike-slip component in the fault movement. However, it is difficult to determine the exact nature of the stress involved in the fault reactivation.

Multiples and noise on the seismic data makes it difficult to observe the continuation of the fault into the Paleocene. However, it is clear that Paleogene sediments in the Hammerfest Basin were lifted up before cut by glacial erosion during the Pleistocene (Figure 10).



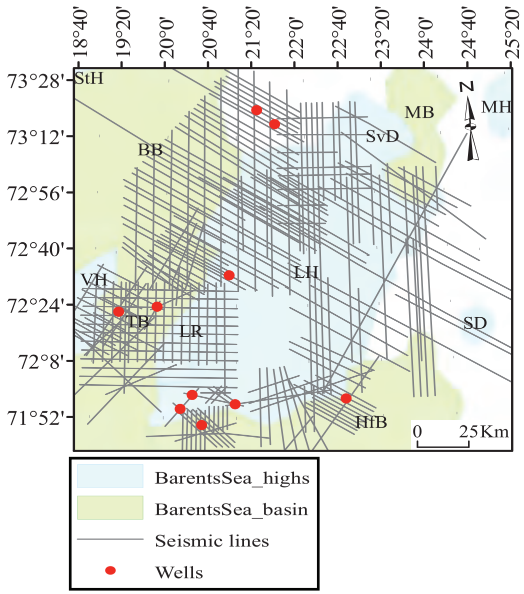


Figure 21. Structural map of Base Cenozoic subsurface in TWT, showing fault family 1 and 2, structural features and erosional boundary.

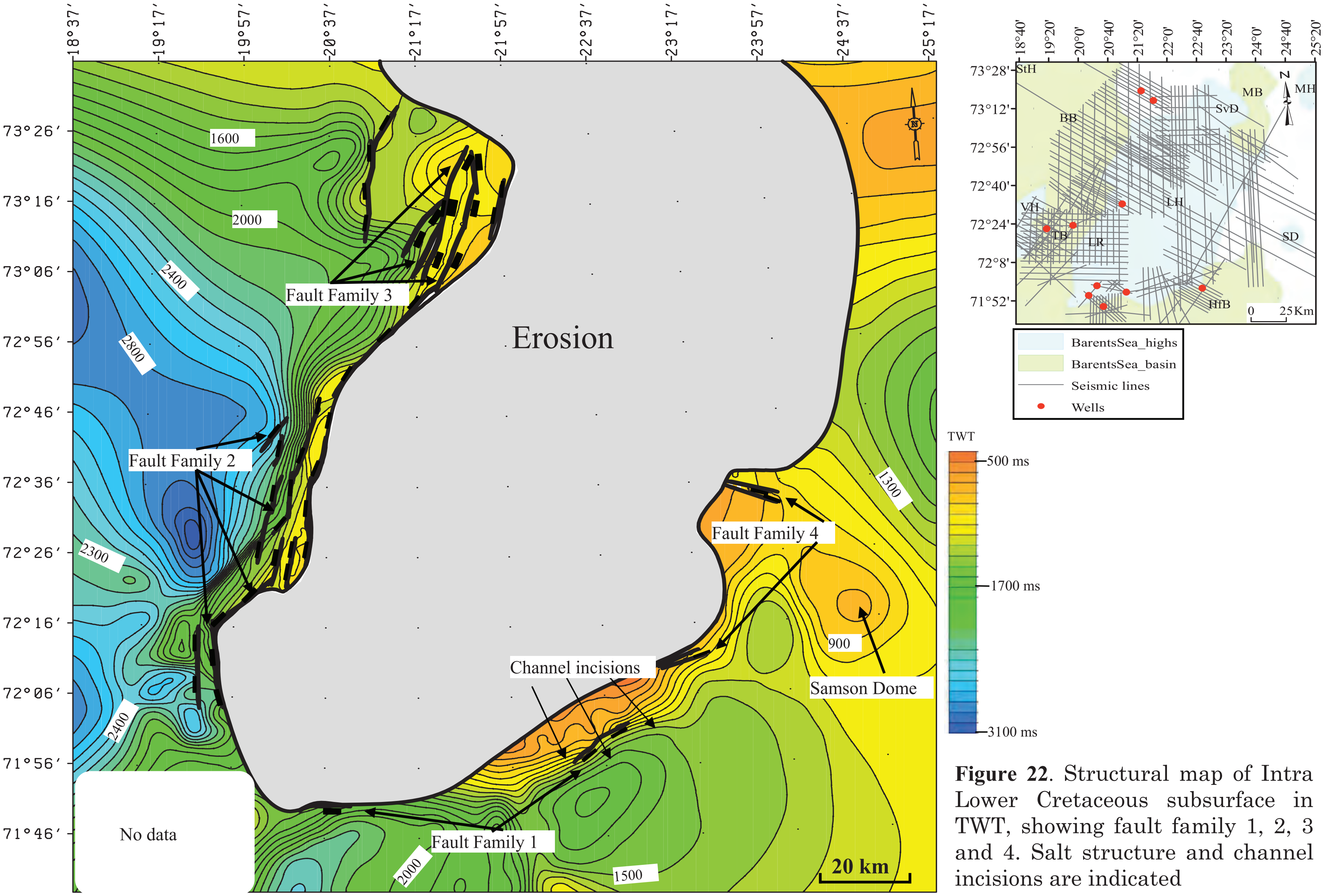


Figure 22. Structural map of Intra Lower Cretaceous subsurface in TWT, showing fault family 1, 2, 3 and 4. Salt structure and channel incisions are indicated

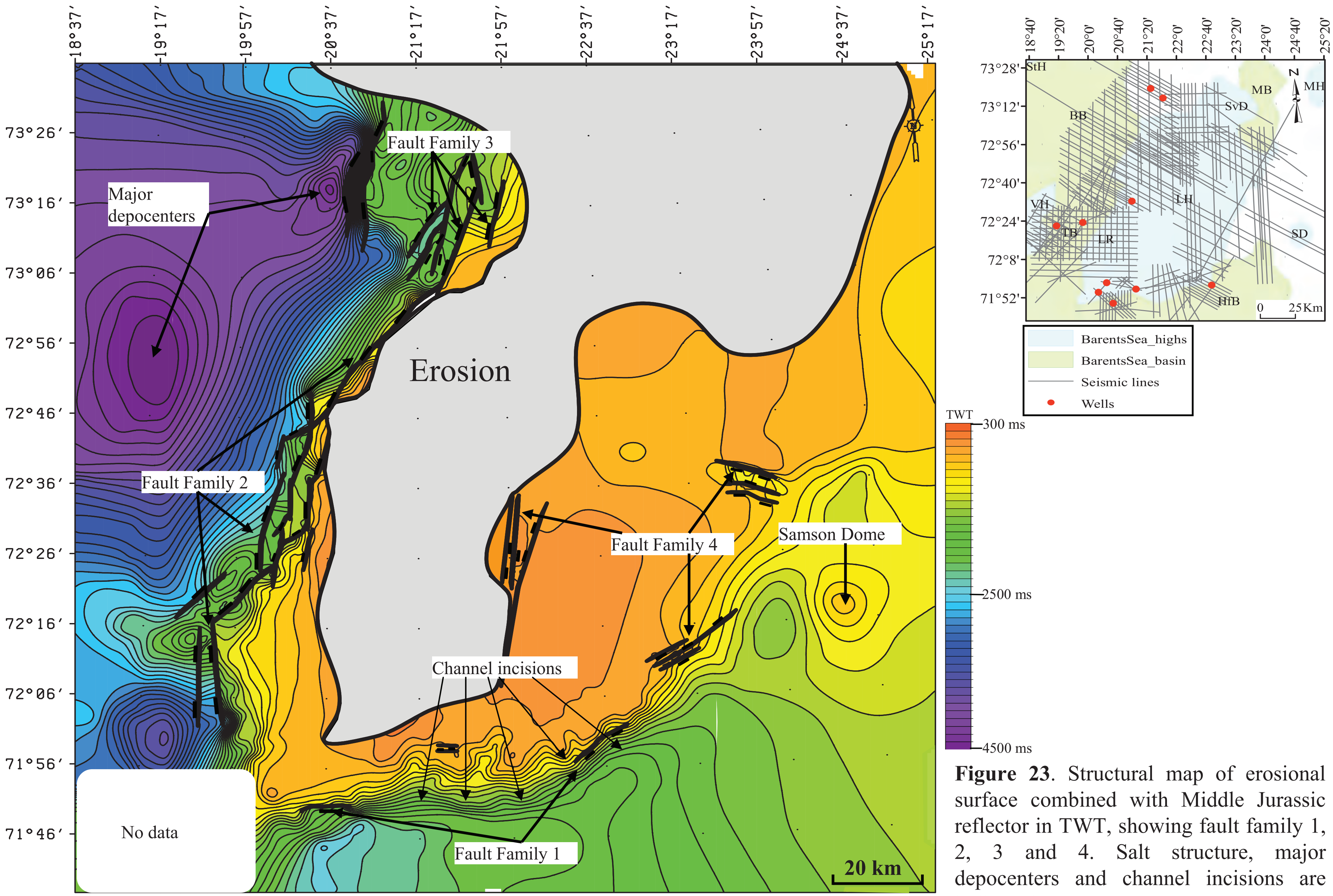


Figure 23. Structural map of erosional surface combined with Middle Jurassic reflector in TWT, showing fault family 1, 2, 3 and 4. Salt structure, major depocenters and channel incisions are indicated

Fault Family 2

Fault family 2 comprises extensional fault blocks that separate the Loppa High from the deep Tromsø and Bjørnøya Basins. The faults have N-S and NE-SW strike with west dip and are part of the Ringvassøy-Loppa High Fault Complex and Bjørnøyrenna Fault Complex, respectively (Figure 11, 12, 13, 16).

Southwestern part of the Loppa High. In the Polheim subplatform, the low-angle normal faults were reactivated in the Early Cretaceous after the Late Jurassic large-scale rifting event, which caused basin subsidence (Figure 11). This reactivation phase was associated with syn-rift deposition of the Barremian sequence and fault block rotation associated with footwall uplift. Aptian - Albian sequence was affected by Early Cretaceous tectonic activity showing the constant strata growth towards the Tromsø Basin (Figure 12).

Northwestern part. Bjørnøyrenna Fault Complex is characterized by high angle normal faults with large downthrows dipping to the northwest (Figure 13, 16). Like in the Polheim subplatform, faults in Bjørnøya Basin experienced footwall rotation and fault footwalls were exposed to erosion while the Loppa High was uplifted during the Barremian tectonic activity (Figure 13, 16). Fault reactivation during the Late Cretaceous affected the Lower Cretaceous succession. Similar to the southeast, the Aptian-Albian sequence is truncated by Late Cretaceous strata. The Paleogene sequence is deformed by the Cenozoic deformation phase. In figure 13, the Paleogene sequence is tectonically uplifted and has the monoclinal dip towards the Bjørnøya Basin. From observations, it is difficult to establish the nature of the deformation phase and not possible to name the exact age of this deformation phase. However, this tectonic reactivation of the fault complex must have happened after the Paleogene sediments were deposited. This tectonic effect can also be observed on the structural map (Figure 21).

Fault family 2 separates the Bjørnøya Basin from the distinct western crest of the Loppa High that has experienced significant tectonic activity and deformation (Gabrielsen et. al., 1990, Faleide et. al. 1993). The western crest is underlain by the shallow metamorphic basement having a triangular or trapezoidal shape that can easily be noticed by its chaotic, discontinuous, and low-amplitude reflectors (Figure 10).

Fault Family 3

This fault family is located in the Fingerdjupet Subbasin, in the northwest of the Loppa High (Figure 9). A system of NNE-SSW - striking faults with dips to the east defines this fault family, which contains a major horst along the western part of the subbasin. According to Gabrielsen et. al. (1990), Late Jurassic tectonism generated the dominant fault trend. However, the Early Cretaceous tectonic phase activated this fault family by footwall uplift, like in the rest of the study area.

The western part of the Loppa High has been affected by the fault family and has a characteristic domal signature. Carboniferous – Permian carbonate/evaporite layers are rather thick, what makes it difficult to observe the basement core. This fact makes the principal difference between the fault family 2 and 3.

Fault Family 4

This fault family is represented by SW-NE and NW-SE striking grabens and half-graben structures located in the central part and on the southeastern platform of the Loppa High (Figure 15, 16, 20). It has been proposed that structures started to develop during the Middle Jurassic or earlier (Gabrielsen et. al. 1990). According to seismic interpretation performed in this study, the fault family 4 has been active during the Early Cretaceous as well. The deposition of the sequence 1 on the northeastern flank of the Loppa High was interrupted by the activity of this fault family (Figure 15 &16). The grabens affect mostly the Triassic succession, strata below the Carboniferous-Lower Permian evaporates do not seem to be affected (Figure 15, 16 & 20). The fault family does not have the significant impact on the tectonic evolution of the study area. However, the fault family is marked on the structural maps (Figure 22 & 23).

Erosion phases

Based on the seismic interpretation and observations, several erosional phases can be identified according to unconformities and onlap/truncation relationships between the sequences. These erosional events are summarized in the figure 24.

Early Cretaceous erosional phase

This erosional surface was developed due to significant uplift of the Loppa High during the Barremian. Therefore, the surface is represented over a large area (Figure 24). This unconformity is characterized by the Lower Cretaceous (Aptian-Albian) sequence that overlies the Triassic succession on the southeastern and southwestern flanks of the Loppa High. Here, the erosional surface represents the major stratigraphic break. On the northwestern flank of the Loppa High, erosional event was the response due to the footwall uplift and its rotation. Based on the seismic regional profile, it is possible to estimate missing section of the Triassic succession and its overlaying Barremian sequence (Figure 25 & 26). Using the seabed as the base and pink dashed line as the top of the interval, the estimated thickness of sediments that are missing is 300-400 m (using 2000 s/m as the average velocity of the sediments). This is the maximum thickness of the sediments that are missing on the top of the Loppa High.

Late Cretaceous erosional phase

This erosional phase was a result of renewed tectonic activity during Late Cretaceous that caused the uplift of the Loppa High. This erosional event is characterized by truncations of the Late Cretaceous strata (Figure 10) and angular unconformity of the Aptian-Albian sequence (Figure 16). In the southeastern flank of the Loppa High, the Late Cretaceous Strata are poorly preserved and is difficult to trace. On the western part of the study area, the Strata are slightly thicker but are truncated by overlaid Base Cenozoic reflector. In order to estimate missing sedimentary column, over the Loppa High and in the Fingerdjupet subbasin, we use regional transects with the well data (Figure 25 & 26) and the Aptian - Albian succession.

On the Loppa High (well 7220/6-1), the Aptian-Albian sequence is represented and onlaps against the fault block. Using the seabed as base and heavily bent Base Cenozoic reflector (green dashed line) reconstructed over the Loppa High as the top of the interval, we estimate the missing section of the Aptian - Albian sequence to be equal ca. 600 m (Figure 26).

In the Fingerdjupet Subbasin, Aptian – Albian sequence is not preserved , but can be defined as the sequence between the Base Pleistocene reflector and Barremian reflectors in the well (7321/8-1, Figure 8). Since we do not know the top of the Aptian-Albian sequence on the following seismic profile, it is not possible to reconstruct sequence for the sediment thickness. However, it is feasible to assume the reasonable value for the thickness estimate (as an average product of the sequence thickness in the Hammerfest Basin (Figure 10) and the thickness of the sequence in the east flank of the Loppa High (Figure 26) to be ca. 800 m. This is the total amount of the Aptian-Albian sequence that is missing on this line. Further, we assume that ca .150-200 m with Aptian-Albian sequence that is preserved in the well 7321/81. Therefore, it was established that thickness estimate for the Aptian-Albian sequence that is missing in the well is c. 600 m.

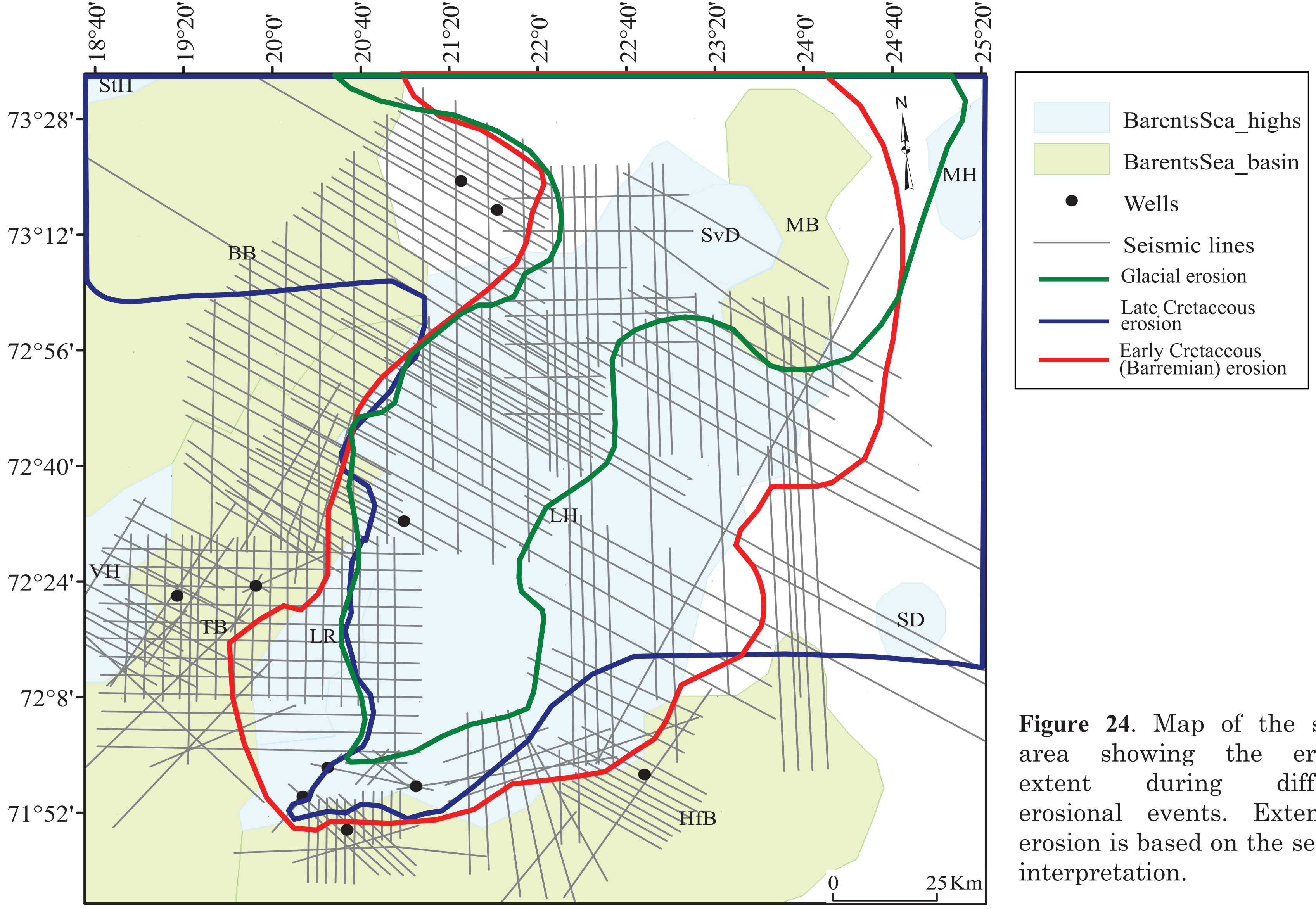


Figure 24. Map of the study area showing the erosion extent during different erosional events. Extent of erosion is based on the seismic interpretation.

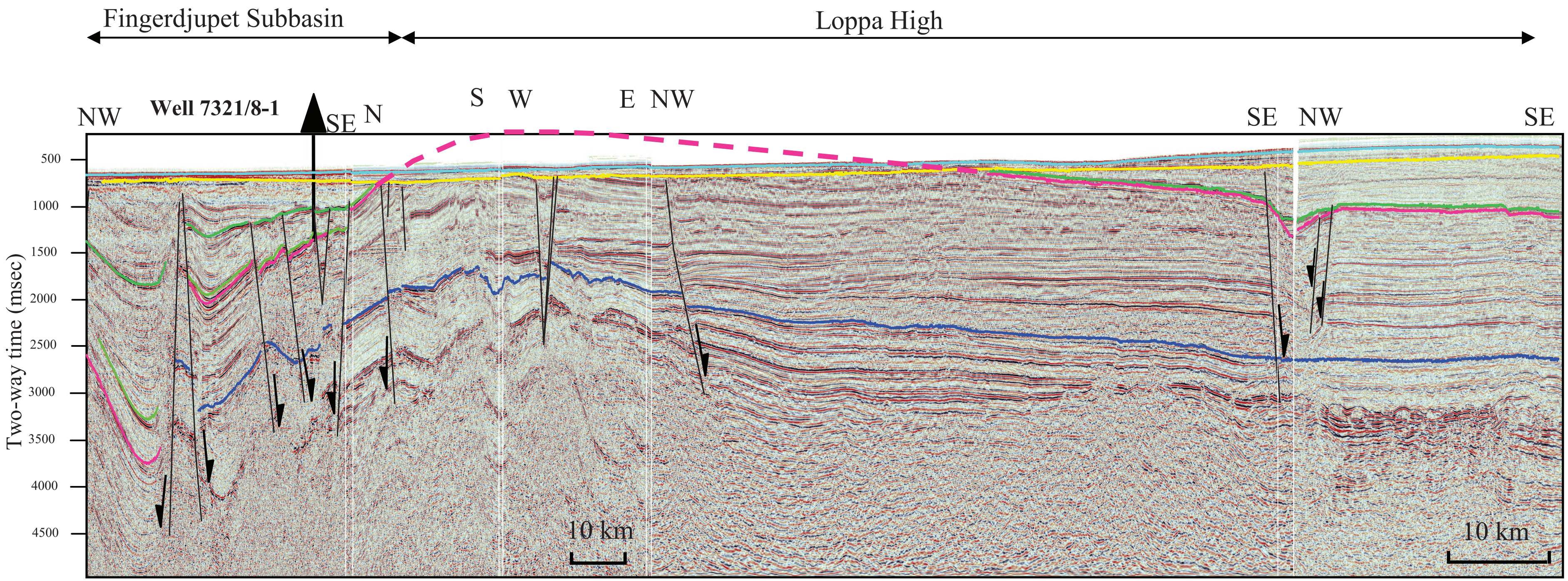
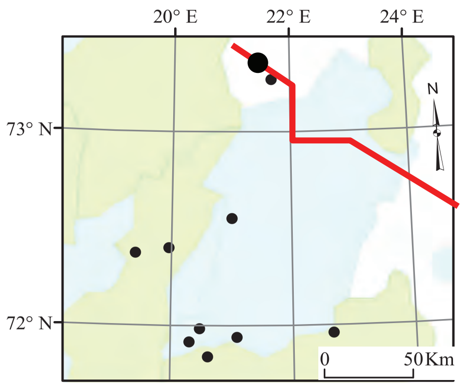


Figure 25. Reconstruction of the Triassic succession that has been eroded during the Early Cretaceous phase. Pink dashed line represent Triassic-Early Cretaceous sediment column.



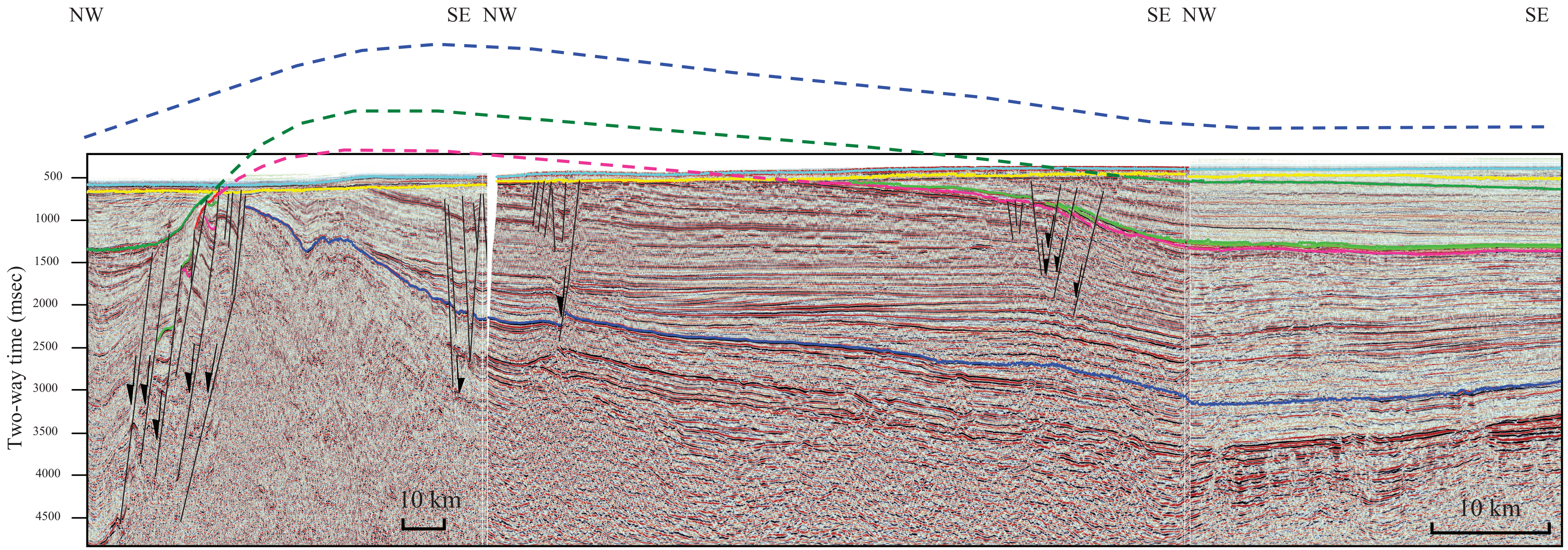
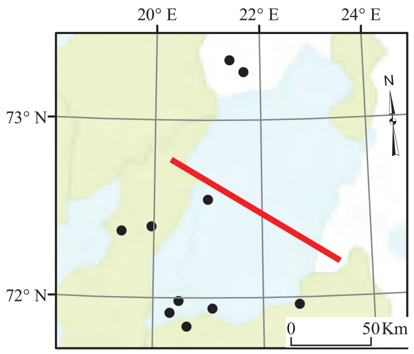


Figure 26. Reconstruction of the Triassic succession that has been eroded during the Early Cretaceous phase. Blue dashed line represent the top of the Paleogene sequence, green- Late Cretaceous succession and pink- Triassic-Early Cretaceous sediments.



Paleogene erosional phase

Several authors refer to Eocene and Oligocene erosion as major erosion events in the Barents Sea during the Cenozoic time (Nyland et. al., 1992, Vågnes et. al. 1992, Reemst et. al., 1993 and Cavanagh et. al., 2006). However, because of the glacial erosion, none of these events is possible to establish using the seismic dataset in the given study area. Therefore, the Early Cenozoic erosional phase is referred to as Paleogene. The uplift and erosion of the Barents Sea during this period had the direct effect on the Paleogene strata represented on the study area. As observed on the seismic data, the Paleogene succession represented mostly on the western flank of the Loppa High has been heavily uplifted ca. 700 msec and eroded during the Paleogene deformation phase.

From the vitrinite reflectance plot, it is ca. 1000 m of sediment difference between the Hammerfest Basin and the well 7321/8-1, summing in 2000 m. Leksnes in her work modeled the erosion of 1300 m for the well 7220/6-1 (Leksnes, 2008). Using these data, the thickness estimate for the Paleogene succession can be determined in seismic profiles 25 & 26.

In the Figure 26, it was calculated 300 m with Triassic sediments and 600 m with Late Cretaceous. However, it is known that the total thickness of the missing layers on the top of the Loppa High is 1300 m. After some basic calculations, it is evident that it is not possible to have more than 400 m with Paleogene sequence on the top of the high.

With 2000 m of erosion in the well 7321/8-1, 400 m with Triassic sediments and ca. 600 m with Aptian-Albian sequence, it can be established that the Paleogene succession was ca. 1000 m thick. Comparing estimated thickness of the Paleogene layers, it is clear difference of 600 m in sequence thickness.

Pliocene-Pleistocene erosional phase (Glacial erosion)

This erosional phase is characterized by glacial subsurface, which is represented over the entire study area (Figure 27). This phase of the erosion is caused due to number of glaciations undergone during last 2.5 Ma. This erosional phase has the most intense erosional character since three sequences described above are truncated by this glacial erosional surface (Figure 15, 16). Figure 23 reveals that erosion is more significant in the northern part of the study area and is less pronounced in the southern part of the Loppa High. That is due to northwestern Barents Shelf uplift during the Neogene time (Figure 2).

Vitrinite Reflectance Analysis

The maturity of the vitrinite reflectance is sensitive to time and temperature range. The temperature depends on the heat flow and maximum burial depth. Therefore, it is critical to establish the correct maximum burial depth in order to estimate the sediments exhumation column. To estimate the amount of the sediments that have been eroded using the vitrinite reflectance analysis, it has been assumed that heat flow and burial history for the wells 7321/8-1 (Bjørnøya Basin) and 7220/6-1 (Loppa High) was rather equal. This is quite reasonable assumption because the high-basin contrast is compensated by thickness difference of Paleogene layers. In other words, the thick layers of Paleogene observed west of the Loppa High (Figure 26) once covering the high were buried deeper that thin layer of the same sediments on the high.

Using the depth vs. vitrinite reflectance plot, it is possible to give an estimate of the amount of sediments that are missing in the wells. The vertical distance between the well trends gives an approximation of the amount of sediments that had once been overlying the present strata. According to Cavanagh (Cavanagh et. al., 2006), ca. 900-1000 m of erosion was estimated in the Hammerfest Basin (well 7120/9-1) during the Oligocene-Miocene.

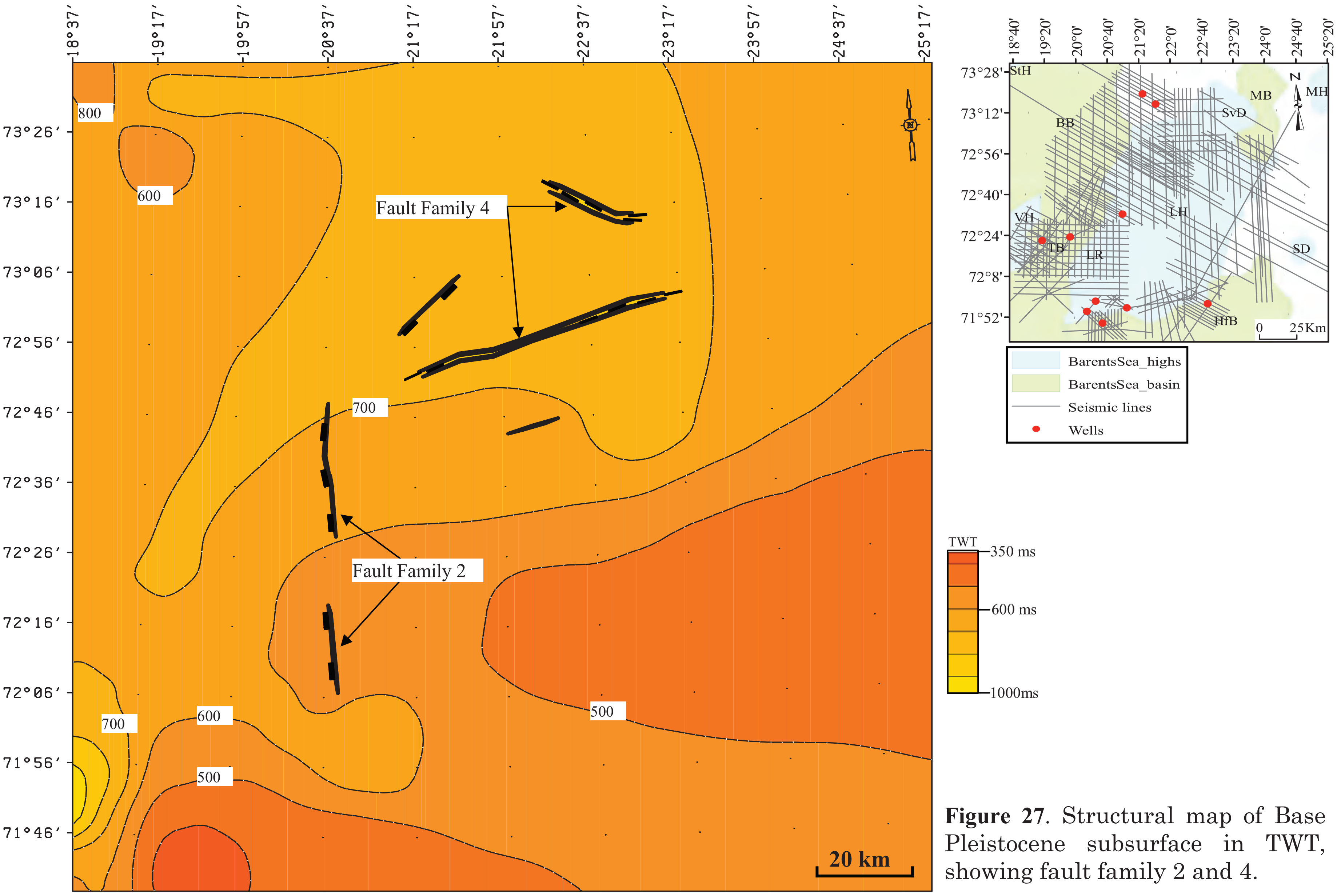


Figure 27. Structural map of Base Pleistocene subsurface in TWT, showing fault family 2 and 4.

DISCUSSION

Vitrinite data vs. estimate of erosion from seismic observation

The amount of erosion, based on the seismic observations, was estimated mostly for the western part of the study area where uplift and erosion rates are most significant. Paleogene layers show significant difference in two reconstructed seismic profiles. Figure 26 shows the NW - SE seismic transect crossing the Loppa High close to well 7220/6-1. Modelling for the erosion estimate gave the following results: Early Cretaceous erosional phase - 300 m, Late Cretaceous erosion ~ 600 m and Paleogene erosion ~ 400 m. In sum, these data give ~ 1300 m of erosion estimate over the Loppa High. In the well 7321/8-1, the Paleogene sequence thickens to be ca. 1000 or more.

The thickness difference between these two wells could be explained space needed for deposition: the 400 m of the Paleogene were deposited in the western crest of the Loppa High that have less space for sediments than Fingerdjupet Subbasin that is deep enough for deposition of 1000 or more Paleogene sequence (Figure 25). In addition, the western part of the Loppa High (Figure 26) could be uplifted and stood emergent Early in the Paleogene.

Comparing the results achieved during the reconstruction with earlier published vitrinite values, the estimated erosion is in rather good. Cavanagh in his analysis proposed the erosion estimate over the Loppa High has to be ca. 1500 m in order to meet the maturation profile (Cavanagh et. al., 2006). However, he also reports that data used in the model is rather scarce. Therefore, the range in estimate can be explained by this data uncertainty. Further, Wood and co-workers proposed that 500 - 1000 m of early Cenozoic sediments were deposited over the high (Wood et. al., 1989). This range of estimate erosion proposed in this study is consistent with the estimate proposed by Wood and co-workers. However, it is necessary to precise that estimated values achieved in the study give a very rough estimate.

Possible mechanisms of the erosion

Based on the observations performed during this study, it is proposed that three major erosional phases, except the glacial erosion, were caused by tectonically active uplift of the Loppa High.

It is believed that the Cretaceous rifting event, caused by Atlantic rift propagation northwards, followed the zone of crustal weakness running along the western margin of the southwestern Barents Sea. Therefore, fault reactivation along the major fault complexes was observed and documented in numerous publications (Wood et. al., 1989, Dengo & Røssland, 1992, Faleide, et. al., 1993, Gabrielsen, et. al., 1996). During this study, it has been established that the high stood emergent during the renewed Early Cretaceous rifting event. Moreover, the fault reactivation of the Asterias and Bjørnøyrenna Fault Complexes has been confirmed by numerous observations.

Intensive erosion of the study area during the Late Cretaceous probably has two reasons. First, the reactivated fault family 1 and 2 caused the renewed uplift of the Loppa High. Several workers have established that this fault reactivation phase had mostly extensional character, with minor local compression (Gabrielsen et. al., 1990, Faleide et. al., 1993, Gabrielsen et. al., 1996). This phase of the Loppa High uplift occurred simultaneously with Barents Shelf uplift, especially affecting the northern part of the Barents Sea (Figure 2) (Torsvik et. al., 2002, Brekke & Olaussen, 2008). Therefore, the extent of this erosional phase is most significant in the northern part of the study area, and less pronounced in the south (Figure 24). Second, despite global sea-level rise, relative sea-level drop during the Late Cretaceous led to water depths across the southern central Barents Shelf became somewhat shallower (Brekke & Olaussen, 2008). The truncation of the Aptian-Albian sequence on the southeastern and western flanks of the Loppa High and condensed layer of Late Cretaceous Strata might be the result of shallow sea established in the Hammerfest and Bjørnøya Basins.

The last stage of the fault reactivation affected the Paleogene erosion phase can be related to Eocene – Oligocene uplift when inversion and fording reached its maximum due to progressive northwards opening of the North Atlantic and Arctic oceans. Uplift and glacial erosion of the Paleogene succession do not allow us to establish this tectonic phase. However, several workers suggest this period to be the major event in the Cenozoic uplift and erosion caused by sea-level fall (Nyland, et. al., 1992, Faleide et. al., 1993, Reemst & Cloetingh, 1994, Cavanagh et. al., 2006).

Observed from seismic profile, Paleogene sequence, as well, as Base Cenozoic reflector, is heavily bent. Anticlinal shape of western crest of the Loppa High and reactivation pattern of the fault block indicate that deformation had more compressional character rather that extensional.

Petroleum significance

The timing of uplift and erosion is an important factor controlling the generation, maturation, and preservation of hydrocarbons. The generation of hydrocarbons can cease because of cooling during the erosion. In turn, erosion of the sediments can seriously damage the preservation potential of the reservoir or sealing rock. In the worst case, the uplift and erosion destroy the entire petroleum play.

The uplift and the erosion of the Loppa High during Late Mesozoic – Cenozoic had direct consequences for the exploration on the Loppa High. Exploration wells have been drilled on the Loppa High with little success in making a discovery. Therefore, the majority of the wells have been abandoned with residual hydrocarbon shows (www.npd.no). This indicates that hydrocarbons have been generated before they were removed by several events of uplift end erosion started in Early Cretaceous.

This study reveals that a relatively small amount of Cretaceous sediments (up to 600 m) were deposited on the southeastern and western flanks of the Loppa High. Moreover, mapping of the unconformities allows to establish several Cretaceous erosion events and to determine the extent of the erosion. It also has been confirmed that a small amount (400 m) of Paleogene sediments was deposited on the Loppa High before last erosional event, namely the glacial erosion. This observation is important for petroleum potential and future exploration in southwestern Barents Sea since the Loppa High became a sediment source for the adjacent basins (Faleide et. al., 1993).

Conclusions

During this study, the following results were achieved:

1. Major four sequences are identified and described according to main unconformities that define the sequence boundaries. The sequences show variable depositional pattern along the southeastern, southwestern, and western flank of the Loppa High reflecting the complexity in the evolution of the Loppa High since Early Cretaceous.
2. Four main fault families have been identifies according to fault orientation and dip. Fault family 1, 2 and 3 are members of major fault complexes, namely Asterias Fault Complex and Bjørnøyrenna Fault Complex that define the structural boundary between Loppa High and adjacent basins. During this study, it was established that fault families were reactivated several times since Cretaceous times. The most significant fault movements were recorded during the Early Cretaceous (Barremian), Late Cretaceous and during late Paleogene. The latter tectonic phase was difficult to study due to Paleogene sediments that were eroded and do not contain much of the deformation record. The further investigation and dataset that covers larger area are required in order to study this deformation event affected the Loppa High.
3. Four major erosional phases were established and documented in this study. It was established that erosional events are directly affected by fault reactivation phases during the Early Cretaceous, Late Cretaceous, and Late Paleogene. The extent of the erosional phases is documented and the amount of the sediments that are missing was roughly estimated through the seismic reconstruction. The results are compared with the erosion estimate previously established in vitrinite reflectance analysis.

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Survey	Type	Shot for	Shot by	Area	Year	Length (km)
EL-8703	2D	ELF	CGG	LOPPA EAST	1987	2041,832
NH8403	2D	HYDRO	GECO	BJØRN.SYD	1984	1636,714
NH8506	2D	HYDRO	MERLIN	LOPPARIDGE	1985	2908,48
NH8513	2D	HYDRO	GECO	LOPPARYGG	1985	122,972
NH8514	2D	HYDRO	GECO	LOPPARIDGE	1985	907,584
NH8610	2D	HYDRO	GSI	BL7120/2,3	1986	395,986
SG8737	2D	SAGA	GECO	BARENTSSEA	1987	1048,083
SG8962	2D	SAGA	GEOTEAM	BJØRNØYA S	1989	418,329
SG9714	2D	SAGA	NOPEC	LOPPA	1997	603,161
ST8611	2D	STATOIL	WESTERN	LOPAHØY SØ	1986	3870,276
ST8813	2D	STATOIL	WESTERN	LOPPAHØYDE	1988	566,487
ST8823	2D	STATOIL	WESTERN	LOPPAHØYDE	1988	742,118
FWGS-84	2D	STATOIL	GECO	FINN.WEST	1984	3907,842
LHSG-89	2D	STATOIL	GECO	LOPPA.SYD	1989	1802,492

Table 1. Summary of the seismic surveys. Year of acquisition and survey extent.

	7120/1-1	**7120/2-1**	**7120/2-2**	**7120/9-2**	**7121/1-1**	**7122/2-1**	**7219/9-1**	**7220/6-1**	**7321/8-1**	**7321/9-1**
Drilling Operator Name	A/S Norske Shell	Norsk Hydro Produskjon AS	Norsk Hydro Produksjon AS	Norsk Hydro Produksjon AS	Esso Exploration& Production Norway A/S	Norsk Hydro Produksjon AS	Norsk Hydro Produksjon AS	Norsk Hydro Produksjon AS	Norsk Hydro Produskjon AS	Norsk Hydro Produksjon AS
Year of Drilling	1985	1985	1991	1984	1985	1992	1987	2005	1987	1988
Total Depth	2569	3502	2794	5072	916	2120	4300	1540	3482	1800

Table 2. Summary of the well name, year of acquisition and drilling operator name.

7120/1-1	7120/2-1	7120/2-2	7120/9-2	7121/1-1	7122/2-1	7219/9-1	7220/6-1	7321/8-1	7321/9-1	GP / FM	AGE
367	410	360	316	396	386	379	394	491	483	Nordland	Holocene
490	476	437	380	519	418	483				Sotbakken/Torsk Fm	Base Pleistocene
		1443	1072		743					Nygrunnen / Kviting Fm	Int.Upper Cret.(Campanian)
		1450	1097		764	1468		546	558	Adventdalen / Kolmule Fm	Cenomanian
		1948	1847		1764			852	892	Kolje Fm	Aptian
		2120	1871		1832	1836		1352	986	Knurr Fm	Intra L.Cret.U./Barrremian
		2503	1906		1955	1893		1383	1317	Hekkingen Fm	Base Cret. Unconf.(BCU)
		2656	1965		2025	1919		1427	1367	Fuglen Fm	Up.M.Juras.Unconfor.
692	613	2692	1971	698	2068	1951		1437	1379	Kapp Toscana / Stø Fm	Middle Jurassic Unconfor.
			2048			2062		1455	1417	Nordmela Fm	Early Jurassic
			2156			2206				Tubåen Fm	Late Triassic
692			2290	698		2305		1467	1424	Fruholmen Fm	Late Triassic
1106	613		2552	792		2877	476	1626	1572	Snadd Fm	Late Triassic
2285	1933		3962					3362		Sassendalen / Kobbe Fm	Middle Triassic
2315			4245							Klappmyss Fm	Early Triassic
2373			4806							Havert Fm	Early Triassic
2403/ 2458			4844					3398		Tempelfjorden / Ørret Fm	Late Permian
2430			4956					3398		Røye Fm	Late Permian
	1945						1138			Gipsdalen / Ørn Fm	Up.L.Carbon-EarlyPermian
	2024						1436			Falk Fm	Late Carboniferous
	2221									Ugle Fm	Late Carboniferous
	2624									Billefjorden	Early Carboniferous
	3471						1483			Basement	

Table 3. Well tops identified by NPD (www.npd.no)