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Ida Kristine Terjesen Hagen</td><td>…………………………………………
(Writer's signature)</td></tr>
<tr><td colspan="2">Faculty supervisor: Alejandro Escalona

External supervisor(s):</td></tr>
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Late Paleozoic development of the Finnmark Platform, southwestern Barents Sea, Norway

by

Ida Kristine Terjesen Hagen

MSc Thesis

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Abstract

Following the recent Gohta and Alta discoveries in the Loppa High by Lundin Norway AS in 2013 and 2014 respectively, there has been an enhanced interest for the Upper Paleozoic succession in the Norwegian Arctic Shelf region. Several previous studies have confirmed that the eastern Finnmark Platform provides an excellent location for studying evolution of a carbonate platform with changing platform morphology and buildup distribution in space and time. Stratigraphical differences have been noted across the platform; however limited information exists about the Upper Paleozoic succession and its development on the central and western platform, in comparison to on the eastern Finnmark Platform. In this study, 2D and 3D seismic data have been combined with well data in order to develop a regional understanding of the Late Paleozoic development of the entire Finnmark Platform. The aim is to improve the paleogeographic understanding of the region by obtaining knowledge about the architecture of the Upper Paleozoic carbonate succession across the platform, define structural and stratigraphical boundaries, and determine controlling mechanisms responsible for observed varying sedimentation patterns. Enhanced knowledge about the historical development of the Finnmark Platform in space and time is beneficial for an improved understanding of the extension of the Late Paleozoic carbonate platforms, as well as the geological evolution of the area.

Significant differences, both structurally and stratigraphically, have been observed across the platform. Consequently, three provinces could be defined. The eastern province represents a stable platform dominated by Upper Paleozoic warm- and cold-water carbonate buildups and deposits. These carbonate units are observed to pinch-out towards a fault-controlled structural high in the central province. The structurally complex western province is dominated by clastic sediments. Late Paleozoic marine incursion from the east, responsible for development of favorable conditions for carbonate buildup growth and deposition in the east, did neither reach the western, nor most of the central province. During the Late Carboniferous-Early Permian times, these areas represented a positive subaerially exposed feature and were not site for deposition. Indications of Early Permian marginal uplift, similar to what has been reported from Bjørnøya, have been observed and seem to have influenced the overall depositional regime on the Finnmark Platform at the time. Eventually, in the late Early Permian, the central and western provinces became submerged. Spiculites were deposited across the entire Finnmark Platform, although presumably under contrasting depositional settings.

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Chapter 1: Introduction

Over the last 40 years, scientists have studied the Upper Paleozoic carbonate successions of the Arctic regions of northeast Greenland and Norway. Discoveries of prolific hydrocarbon reservoirs in Late Carboniferous and Permian carbonate strata elsewhere in the world have been a major motivating, and inspiring factor for the extensive investigation (Colpaert et al., 2007). The recent Gohta and Alta discoveries in the Loppa High by Lundin Norway AS in 2013 and 2014 respectively, have confirmed that the Late Carboniferous and Permian carbonate succession also has a significant reservoir potential in the Barents Sea (Stemmerik et al., 1999; Elvebakk et al., 2002). Consequently, there has been an enhanced interest for the Upper Paleozoic succession, which nowadays acts as an important play model in the Norwegian Arctic Shelf region (Rafaelsen et al., 2008).

The Finnmark Platform (Figure 1) provides an excellent location for studying the evolution of a carbonate platform with changing morphology and buildup distribution in space and time. During the Late Paleozoic, the Finnmark Platform was part of a wide carbonate system that covered the entire Arctic shelf region (Golonka et al., 2003). A near complete Upper Paleozoic succession has been encountered by two of the exploration wells (7128/6-1 and 7128/4-1) that have been drilled on the eastern platform. Fingerprints related to shifts in latitudinal position and paleoclimate, regional changes in relative sea level and paleohydrographic conditions are left within the depositional sequences, and can hence reveal crucial information about the evolution of the area.

1.1 Previous work

Over the last two decades, several authors have studied the Carboniferous-Permian succession on the Finnmark Platform. Important stratigraphic and sedimentological knowledge has been obtained from extensive core analysis of samples both from exploration wells and shallow cores (e.g. Bugge et al., 1995; Blendinger et al., 1997; Ehrenberg et al., 1998; Ehrenberg et al., 2000; Ehrenberg, 2004). Moreover, there have also been conducted several studies with a more regional approach comparing the Finnmark Platform with other locations in the Arctic, such as for example the Sverdrup Basin, Spitsbergen, Bjørnøya, and the Loppa High (e.g. Stemmerik, 1997; Larssen et al., 2002; Stemmerik and Worsley, 2005; Worsley, 2008).

Furthermore, several seismic stratigraphic studies have been compiled on the Finnmark Platform:

- Bugge et al. (1995) divided the Upper Paleozoic succession into four main stratigraphic intervals, and defined a total of fourteen seismic units, on the basis of IKU shallow stratigraphic cores and IKU 2D seismic data (Figure 2).
- Samuelsberg et al. (2003) identified five seismic sequences within the Upper Paleozoic succession based on 2D and 3D seismic data, combined with information from four exploration wells and eight shallow cores (Figure 2).
- Colpaert et al. (2007) demonstrated how six seismic units (Figure 2) could be identified by applying advanced multi-attribute analysis of 3D seismic data.
- And finally, Rafaelsen et al. (2008) demonstrated how 3D seismic data (Figure 2) could be applied to reconstruct the evolution of the carbonate buildups in space and time. The buildups were found to be controlled by bathymetry and/or faults.

All the seismic stratigraphic studies just mentioned were mainly conducted based on 3D seismic data combined with well data from the eastern part of the Finnmark Platform (the data used in the different studies can be seen from Figure 2). As a result, although several studies of the Upper Paleozoic succession on the Finnmark Platform, no seismic stratigraphic study incorporating seismic and well data from both the eastern and western part of the platform has been compiled. Four exploration wells, in addition to eight shallow IKU cores, penetrated the Upper Paleozoic succession on the eastern platform, whereas only one exploration well exists on the western platform. Consequently, up until now, limited information exists about the Upper Paleozoic succession and its development on the central and western parts, in comparison to on the eastern part of the Finnmark Platform.

1.2 Objectives

In this study, 2D and 3D seismic data have been combined with well data to develop a regional understanding of the Late Paleozoic development of the entire Finnmark Platform. The objectives of this study are as following:

- Understand the architecture of the Upper Paleozoic carbonate succession across the Finnmark Platform.
- Define structural and stratigraphical boundaries
- Determine the controlling mechanisms responsible for varying sedimentation patterns across the platform.
- Improve the paleogeographic understanding of the region.

Identification of significant geological geometries such as prograding clinoforms, and changes in platform morphologies and carbonate buildups, will enhance the understanding and demonstrate the results of interplay between tectonics, climate, and sea level changes. These factors are key as they determine the sediment accommodation space, which further controls the platform geometries and carbonate buildup development. Enhanced knowledge about the historical development of the Finnmark Platform in space and time is beneficial for an improved understanding of the extension of the Late Paleozoic carbonate platforms, as well as the geological evolution of the area.

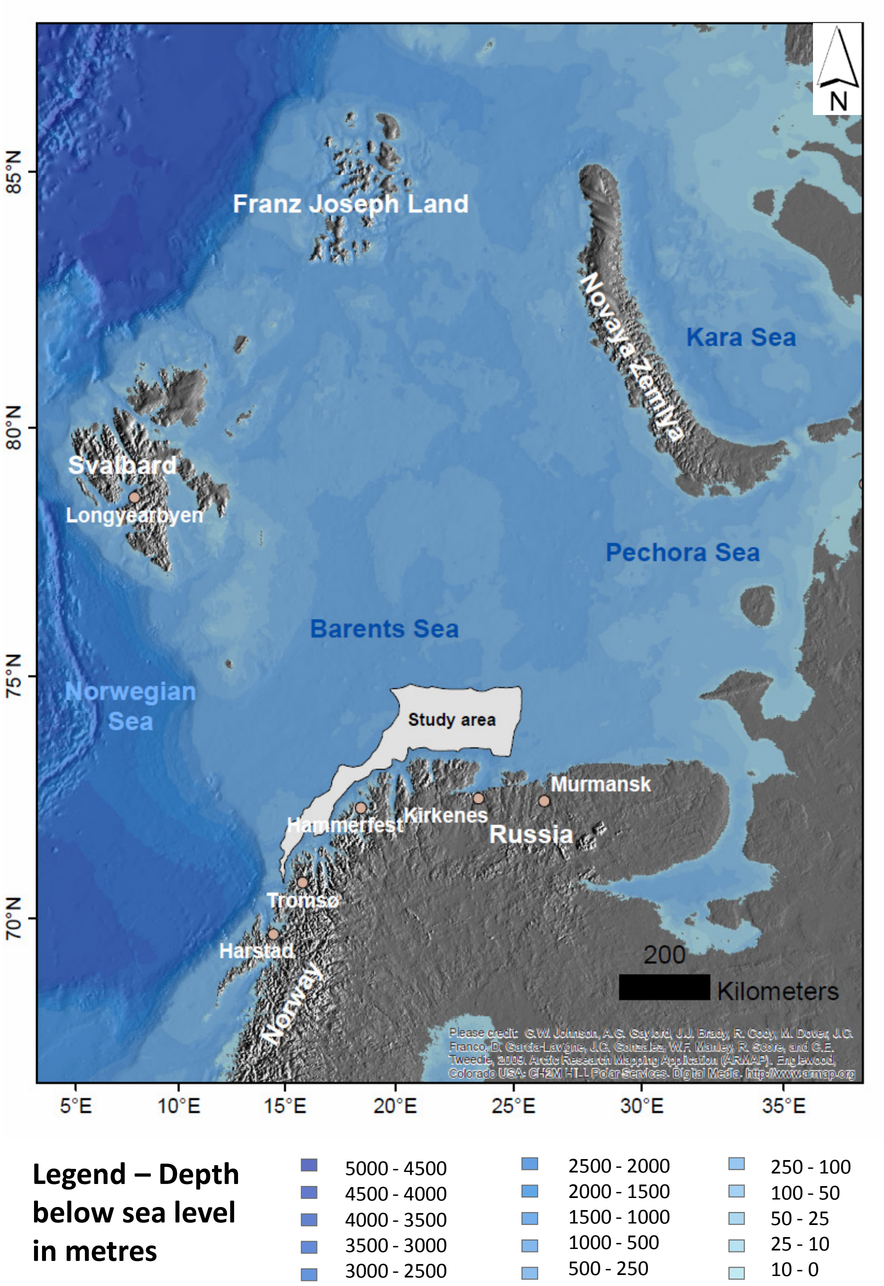


Figure 1: Bathymetry map of the greater Barents Sea. The location of the study area; the Finnmark Platform is outlined.

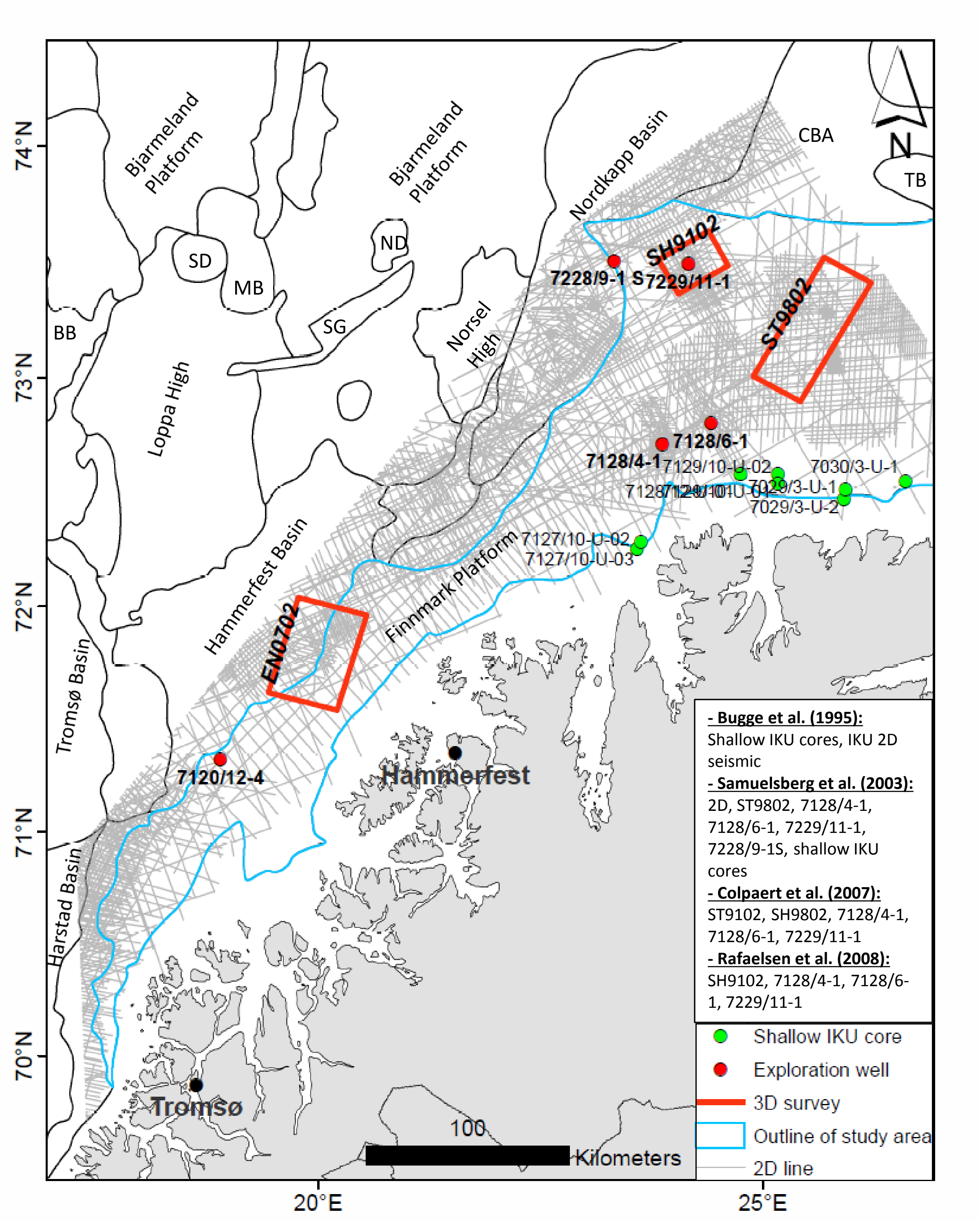


Figure 2: Geological elements of the southwestern Barents Sea. Locations of data used in this study; 3D surveys, 2D lines, and wells are shown. An overview of data used in previous studies can be seen from the uppermost inset. TB= Tiddlybanken Basin, CBA= Central Barents Arch, MB= Maud Basin, SD= Svalis Dome, SG= Swaen Graben, ND= Norvarg Dome, BB= Bjørnøya Basin.

Chapter 2: Geological background

The Barents Shelf is located on the north-western corner of the Eurasian plate and covers an area of approximately 1.3 million km^2 (Worsley, 2008). The Barents Sea represents an intracratonic basin that covers a vast pericontinental shelf area extending from Novaya Zemlya in the east, to the continental slope of the Norwegian-Greenland Sea in the west (Figure 1) (Gabrielsen et al., 1990; Larssen et al., 2002; Halland et al., 2014). The Svalbard archipelago and Franz Josef Land represents the northern delimitation, whereas the Baltic Shield, with the coasts of Norway and Russia, represents the southern (Figure 1). The western and northern boundaries, defined by the Norwegian-Greenland Sea and the Eurasian Basin respectively, both represent passive margins (Larssen et al., 2002).

This study is focused on the Finnmark Platform, which is located in the southwesternmost part of the Barents Sea (Figure 1). The platform is bounded by the Nordkapp and Hammerfest basins to the north (Figures 2 and 3), the Norwegian mainland to the south, and the deep Harstad and Tromsø basins to the west (Figures 2 and 3) (Gabrielsen et al., 1990; Larssen et al., 2002; Samuelsberg et al., 2003; Rafaelsen et al., 2008; Henriksen et al., 2011). The Finnmark Platform represents a relatively stable element of a series of interconnected Late Paleozoic basins and platforms in the Barents Sea, revealing a complex tectonic development resulting from interplay between major tectonic processes operating along the western and north-western margins of the Eurasian plate (Worsley, 2008; Henriksen et al., 2011).

2.1 Tectonic evolution

Through geologic time, several large-scale tectonic processes have affected the southwestern Barents Sea and hence also the Finnmark Platform. The Timanian, Caledonian, Ellesmerian, and Uralian orogenies, in addition to the proto-Atlantic rifting episodes in the west, and the following breakup and opening of the northern North Atlantic along the western margin of the shelf, have been reported as the main tectonic phases responsible for the geological framework of the region (Lawver et al., 2011; Gernigon et al., 2014).

Overall, three prominent structural trends dominate the southwestern Barents Sea; north, north-east and north-west (Figure 3) (Gudlaugsson et al., 1998). The western part is dominated by a north trend (see inset map in Figure 3) confined in a 100 km wide zone east of the continent-ocean boundary, while the north-east trend is confined to the central and eastern parts, including the Finnmark Platform (Figure 3) (Gudlaugsson et al., 1998). A dominant north-west structural trend has been reported for the southeastern part (Figure 3) (Gudlaugsson et al., 1998).

2.1.1 Precambrian

In the Ediacaran time, the Timanian Orogeny developed along the northeastern passive margin of Baltica, resulting in development of a fold-and-thrust belt in the southeastern Barents Sea (Gernigon et al., 2014). The Timanian Orogeny had major influence on the basement configuration of the eastern Finnmark Platform (Roberts and Siedlecka, 2002), and resulted in formation of NW-SE oriented structures (Samuelsberg et al., 2003).

2.1.2 Early Paleozoic (Early Cambrian – Late Devonian)

Near the end of the Middle Ordovician, Baltica experienced a rapid increase in velocity and started to converge towards the relatively stationary Laurentia (Figures 4A and 4B), resulting in the Caledonian Orogeny (Lawver et al., 2011). Figure 4B shows that closure of the Iapetus Ocean resulted in Caledonian deformation along Scandinavia and Greenland, and thus also affected the southwestern Barents Sea (Golonka et al., 2003; Lawver et al., 2011; Gernigon et al., 2014). As a result of the Caledonian Orogeny, the western parts of the Barents Sea, including the Finnmark Platform, were uplifted and eroded (Henriksen et al., 2011). The main arm of the Caledonides represents an extension of the Scandinavian-Greenland Caledonides and is thought to cover most of the southwestern Barents Sea (Figure 4B). It follows a general northeast trend (Figure 4B) (Henriksen et al., 2011) and concurs with the observed NE-SW oriented Caledonian structures on the Finnmark Platform (Samuelsberg et al., 2003). The Caledonian Orogeny terminated by the end of the Silurian (416 Ma), when Laurentia and Baltica were welded together and formed Laurussia (Figures 4B and 4C) (Lawver et al., 2011). At the end of the final stage of contraction of the Caledonides, the strain field in the upper crust went from contraction to extension (Golonka et al., 2003).

During the Middle and Late Devonian (Figure 4C), Laurussia experienced a sudden change to more rapid northward motion, at the same time as Siberia started a slight southward motion. It is likely that the Late Devonian to Carboniferous Ellesmerian Orogeny resulted from collision of Siberia with the northern margin of Laurussia (Lawver et al., 2011).

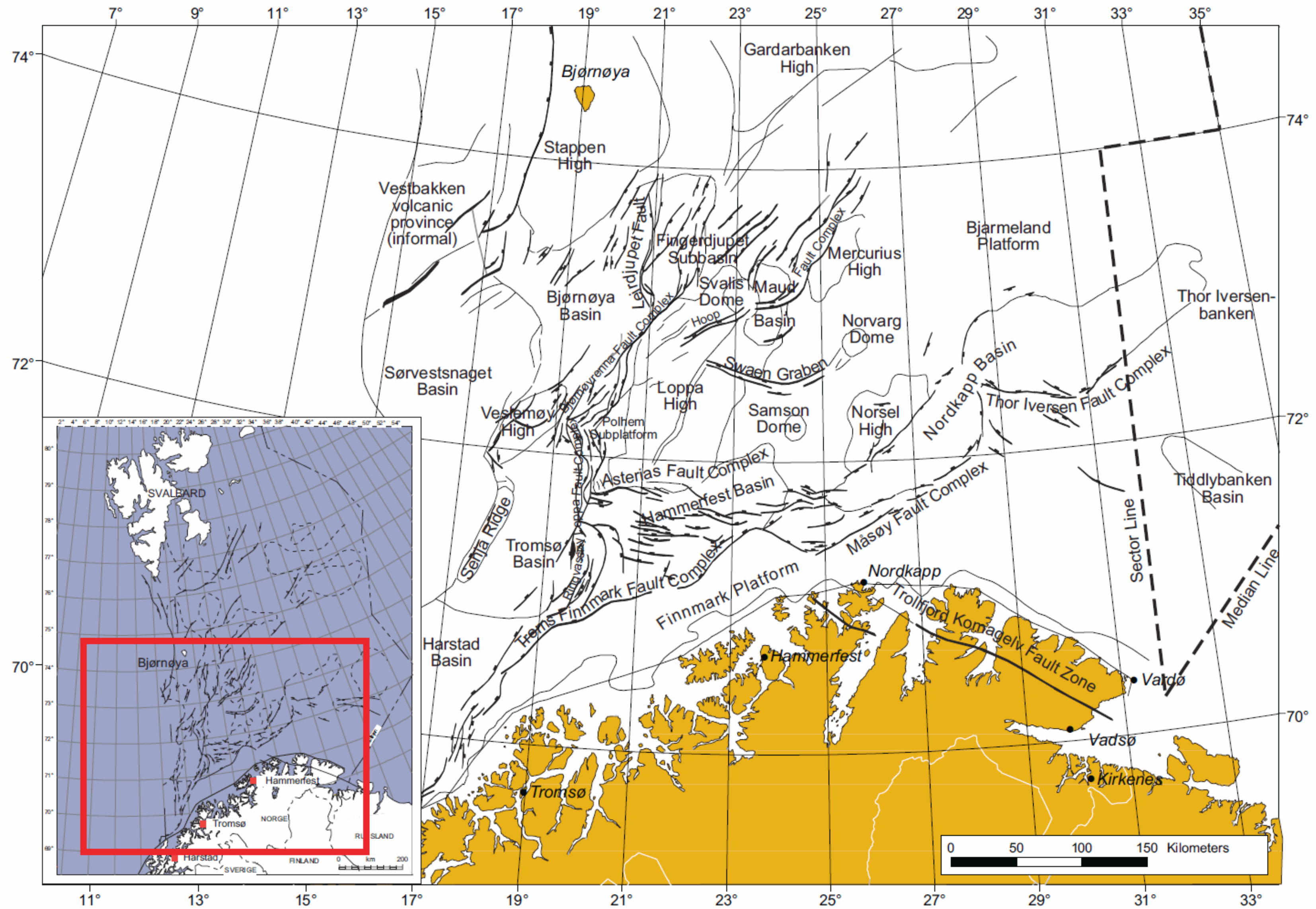


Figure 3: Main structural elements of the southwestern Barents Sea. Note the dominant north structural trend in the west (see inset map), north-east trend in the central, and north-west trend in the east. From Larssen et al. (2002).

2.1.3 Late Paleozoic (Early Carboniferous – Late Permian)

During the Middle Mississippian, the assemblage of the future Arctic blocks, in addition to Gondwana, began a relatively rapid eastward motion (Lawver et al., 2011). Siberia had a slightly faster eastward motion, which resulted in later collision with Baltica (Figures 4D and 4E). The rapid motion of the future Pangea pieces was significantly reduced around 306 Ma, associated with the final closure of the Rheic Ocean and amalgamation of the Pangean supercontinent (Figure 4D) (Lawver et al., 2011). A northward drift took place during the Permian (Figures 4D and 4E), and as a result, the Barents Sea region, including the Finnmark Platform, was brought to approximately 45°N (Figure 4E) (Samuelsberg et al., 2003; Stemmerik and Worsley, 2005). By the end of Permian, the Pangean supercontinent was assembled (Figure 4E).

In the Late Paleozoic, the Finnmark Platform, together with the rest of the Barents Sea region, was part of a vast, roughly east-west oriented continental shelf extending from the Sverdrup Basin (Arctic Canada) in the west, through the northern Greenland, into the Norwegian and Russian Barents Sea, and all the way to the Arctic Russia in the east (Figure 5A) (Larssen et al., 2002; Rafaelsen et al., 2008). This vast province represented the northern margin of Pangea and was characterized by a series of rapidly subsiding intrashelf basins, some of huge dimensions (e.g. the Nordkapp and the Sverdrup basins) (Stemmerik, 2000; Larssen et al., 2002; Rafaelsen et al., 2008). These basins formed a network of grabens and half-grabens, resulting from widespread intracratonic rifting that dominated the Late Devonian to Mid-Permian times (Stemmerik, 2000; Worsley, 2008).

Early Carboniferous rifting resulted in formation of a fault-controlled structural high. Originally, the structural high was separated from the southern Finnmark Platform. However, over time, a fault-controlled saddle area evolved and the highs were linked together (Rafaelsen et al., 2008). The southwestern part of the Finnmark Platform was characterized by extensive development of graben and half-graben style basins, whereas there is no evidence of Viséan rifting eastwards on the platform (Stemmerik and Worsley, 2005).

Regional uplift and associated erosion occurred in mid-Serpukhovian to mid-Bashkirian as basin subsidence and sedimentation ceased (Stemmerik, 2000). Following this regional uplift, renewed rifting and basin subsidence took place during the mid- to late Bashkirian. A 300 km wide rift zone comprising two linked rift arms developed; the Atlantic rift arm between Greenland and Norway, which extended across the central Barents Sea in a northeasterly direction, and the west-trending Arctic rift arm, which developed between

Spitsbergen and Greenland (Gudlaugsson et al., 1998; Stemmerik and Worsley, 2005). Fault-controlled subsidence and depocenters, predominantly with half-graben geometries, formed along the rift axis and have been identified both in the southwestern Barents Sea and on the eastern Finnmark Platform (Stemmerik and Worsley, 2005; Henriksen et al., 2011).

In addition to the fault-bounded basins, more stable intervening platform areas such as the Finnmark Platform were formed as a result of several phases of compression and rifting (Stemmerik, 2000; Colpaert et al., 2007). The fault zone, which is bounding the Finnmark Platform to the north (Figure 3), was active throughout the Late Paleozoic (Samuelsberg et al., 2003).

The late Bashkirian to early Moscovian rifting was followed by regional subsidence and lower rates of sedimentation during the late Moscovian to Gzhelian (Stemmerik, 2000). This Late Carboniferous regional subsidence led to development of a regional sag basin comprising most of the current Barents Shelf (Gudlaugsson et al., 1998; Henriksen et al., 2011), and was likely related to the closure of the Uralian Ocean along the eastern margin of Baltica (Henriksen et al., 2011). The opening of the proto-North Atlantic Ocean was initiated between Baltica and East Greenland during the Late Carboniferous-Early Permian times (Golonka et al., 2003).

During the late Early Permian, development of a marine seaway between Norway and Greenland had a significant impact on the marine circulation systems, and cool sea water flooded the Barents Shelf (Henriksen et al., 2011). A widely recognized tectonic event, involving rejuvenation of older lineaments, occurred in the Kungurian (Stemmerik, 2000; Stemmerik and Worsley, 2005), and by the end of Permian, the Uralide Orogeny had resulted in closure of the marine connection to the south.

2.1.4 Mesozoic

During Permian and earliest Triassic time, Laurussia collided with Siberia resulting in formation of Laurasia, which became a part of the Pangean supercontinent (Figure 4E). This collision led to development of the Uralian Orogeny, which affected major parts of the Barents Sea, the eastern areas in particular (Golonka et al., 2003). Stress-release events of very large magnitudes have been dated to the Permian-Triassic boundary. These are probably linked to shifts from convergent to divergent plate tectonics, as crustal uplift and inversion was followed by collapse of the crust (Golonka et al., 2003).

The earliest stages of the Triassic, was dominated by major rifting and rapid subsidence (Henriksen et al., 2011; Gernigon et al., 2014). This rifting phase also involved initial rifting and breakup of the Pangean supercontinent, which further intensified in the Norian time, and led to formation of rift basins and passive margin development (Golonka et al., 2003). Despite this, the Triassic was overall a tectonically relatively quiet period in the western Barents Sea (Figures 4E and 4F) (Henriksen et al., 2011). Passive regional subsidence dominated, and only minor movements have been observed on the Finnmark Platform (Henriksen et al., 2011). Post-rift thermal subsidence became more prominent towards the end of the Triassic (Gernigon et al., 2014).

Middle Jurassic to Early Cretaceous rifting had a pronounced effect on the western margin of the Barents Sea Shelf, including the Finnmark Platform, and resulted in establishment of the present day structural configuration of the region (Henriksen et al., 2011).

2.1.5 Cenozoic

The final lithospheric breakup of the North Atlantic margin, and subsequent opening of the Norwegian-Greenland Sea, occurred around 55-54 Ma, near the Paleocene-Eocene transition (Faleide et al., 2008; Gernigon et al., 2014). The rifting lasted for 3-6 million years and involved massive magmatic activity associated with the onset of early sea-floor spreading (Faleide et al., 2008). Although an overall Cenozoic extensional tectonic dominance, inversion and compressional features, dated to Oligocene-Miocene age, are also found widespread in the Barents Sea (Henriksen et al., 2011).

A following phase of differential uplift, and glacial erosion, had significant impact on the final sculpting of the region (Larssen et al., 2002). This event resulted in the present gentle northward tilt of the Finnmark Platform (Gabrielsen et al., 1990; Larssen et al., 2002; Samuelsberg et al., 2003; Faleide et al., 2008).

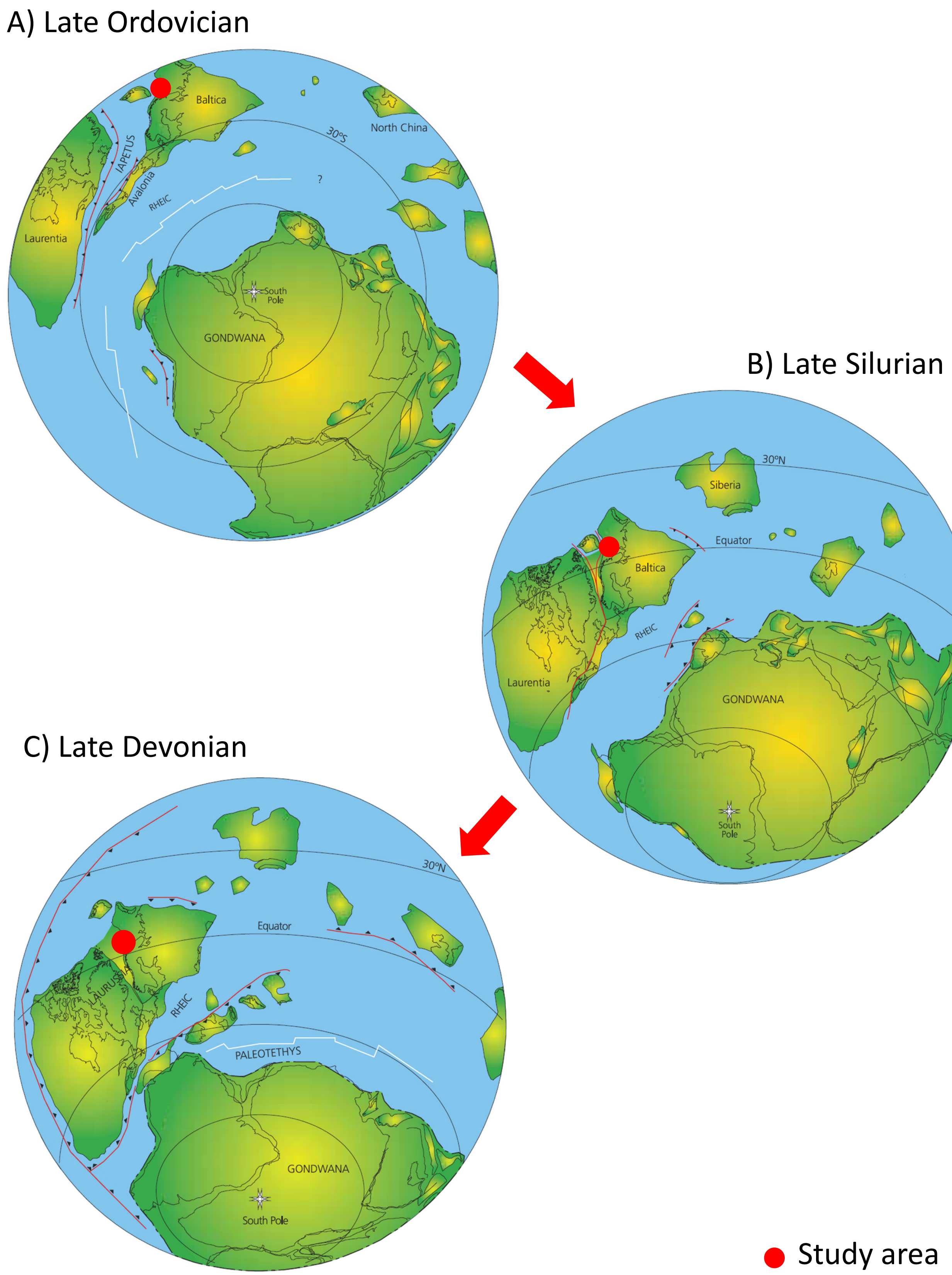


Figure 4: Plate-reconstructions from A) Late Ordovician to F) Late Triassic. The approximate position of the study area is marked with a red dot. Modified from Torsvik et al. (2002).

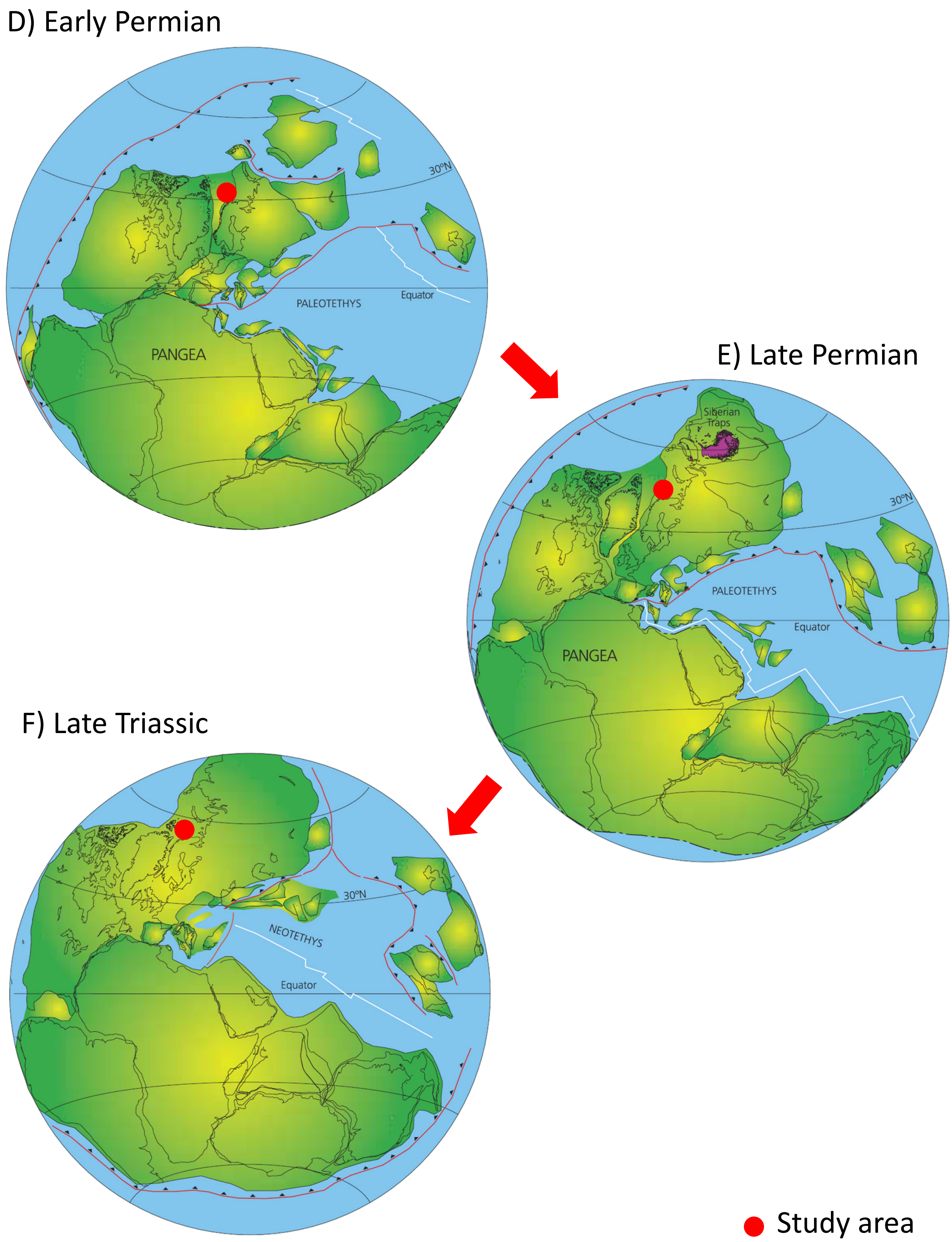


Figure 4. Cont.

2.2 Late Paleozoic stratigraphical evolution

The Upper Paleozoic succession in the Barents Sea reflects a complex interplay of rifting, long-term sea level fluctuations, and changing climate as a result of continuing northwards movement of the northern Pangean margin (Samuelsberg et al., 2003; Worsley, 2008). During the Carboniferous and Permian times, the northern Pangean shelf drifted northwards with a rate of 2-3 mm per year (Stemmerik and Worsley, 2005). In the latest Devonian-Early Carboniferous the shelf was located at an approximately 20°N paleolatitude, while it in the end of Permian had moved to approximately 45°N (Figure 4E) (Samuelsberg et al., 2003; Stemmerik and Worsley, 2005). Stemmerik and Worsley (2005)'s paleogeographic reconstructions of the northern Pangean shelf during the Late Paleozoic presented in Figures 5B to 5F, reveal how the northward latitudinal drift clearly affected the sedimentary regimes and depositional conditions along the entire shelf. The climate gradually changed from being tropical and humid in the Early Carboniferous (Figure 5B), subtropical and dry in the Bashkirian-mid-Sakmarian (Figures 5C and 5D), cool temperate in the late Sakmarian-Kungurian (Figures 5E and 5F), and eventually cold temperate in the Late Permian (Beauchamp and Desrochers, 1997; Stemmerik, 1997, 2000; Stemmerik and Worsley, 2005). Varying tectonic processes along the northern, eastern and western margins of the shelf, combined with short- and long-term local and regional sea-level variations, have had important controls on sedimentation and determined the depositional history of the province (Worsley, 2008). Depositional patterns and faunal assemblages in the Upper Paleozoic succession on the Finnmark Platform, reflect the northward movement of the shelf, which also forms the basis for a lithostratigraphic subdivision of the succession into four groups; Billefjorden Group, Gipsdalen Group, Bjarmeland Group and Tempelfjorden Group (Rafaelsen et al., 2008). Each of these groups represents a second-order sequence with a duration of approximately 15-30 million years (Stemmerik and Worsley, 2005).

2.2.1 Billefjorden Group

In the study area, the Billefjorden Group has been dated to incorporate the Viséan to early Serpukhovian time interval. At this time, the Finnmark Platform was part of a huge humid flood plain extending westward all the way to the Sverdrup Basin (Arctic Canada) (Figure 5B) (Stemmerik and Worsley, 2005). The Lower Carboniferous succession consists mostly of fluvial and lacustrine sediments that were deposited under humid and warm environmental conditions (Stemmerik and Worsley, 2005; Worsley, 2008). Despite the dominance of non-marine sediments, marine shale and shallow marine sandstone deposits have been identified towards the top of the group on the southeastern Finnmark Platform

(Larssen et al., 2002). These findings are indicative of temporary marine conditions, which might have been a result of either an overall global sea level maximum that occurred during the Viséan time (Stemmerik and Worsley, 2005), or presence of a seaway through the Nordkapp Basin, which connected to more open marine environments and that is known to have dominated the eastern Barents Shelf at the time (Worsley, 2008).

2.2.2 Gipsdalen Group

The northern North Atlantic and Arctic, including the Finnmark Platform, was affected by a regional uplift during the Serpukhovian times (Samuelsberg et al., 2003). Consequently, a regional unconformity separates the Lower Carboniferous grey fluvial siliciclastics with coals (Billefjorden Group) from the overlying red bed facies with caliche (Gipsdalen Group). This major unconformity is associated with a significant change in paleoclimate from warm and humid to warm and arid/semi-arid (Larssen et al., 2002).

The Gipsdalen Group is a complex group dated to incorporate the time interval from late Serpukhovian to mid-Sakmarian (Rafaelsen et al., 2008). Figures 5C and 5D represent the paleogeographic reconstructions at the time, and varying depositional regimes are revealed. The dominant deposits are red-colored siliciclastics and warm-water, often dolomitized and karstified, carbonates (Figure 5C) (Larssen et al., 2002; Worsley, 2008). Evaporites are also significantly represented (Figure 5D) (Larssen et al., 2002). A highly diversified fauna characterizes the warm-water carbonate deposits, with green algae and benthic foraminifera representing some of the most dominant groups. The biotic and abiotic elements are dominantly composed of aragonite or high-Mg calcite, and submarine cement is pervasive (Beauchamp and Desrochers, 1997).

During the Bashkirian, sedimentation resumed in localized half-grabens and syn-rift siliciclastics representing arid alluvial fan and braided river deposits accumulated (Larssen et al., 2002; Samuelsberg et al., 2003). Following, in the latest Bashkirian-Kasimovian, the Finnmark Platform was gradually transgressed. A shallow marine depositional setting evolved, characterized by an up-section change in depositional style from mixed siliciclastics and carbonates towards pure carbonates (Samuelsberg et al., 2003).

By the late Moscovian, the relative sea level had risen sufficiently to submerge the southern shelf margin and structural highs (Stemmerik and Worsley, 2005), and a wide, 3000 km long, east-west oriented marine shelf extending from Arctic Russia to Arctic Canada was formed (Beauchamp and Desrochers, 1997; Samuelsberg et al., 2003). From this time, and until the Early Permian times, the Earth was characterized by icehouse conditions, associated with high-frequency and high-amplitude sea level fluctuations (Stemmerik and Worsley, 2005). Ice sheet waxing and waning of the southern Gondwana continent is thought to have been the triggering factor for these significant sea level fluctuations (Colpaert et al., 2007).

The early Gzhelian was characterized by high glacioeustatic sea level, and the central part of the northern Pangean shelf formed an extensive tropical to subtropical, warm-water carbonate shelf (Figure 5C). At this time, the Finnmark Platform likely represented a low angle carbonate ramp, which was part of a very wide shallow-water carbonate system (Samuelsberg et al., 2003; Stemmerik and Worsley, 2005; Colpaert et al., 2007).

In late Gzhelian-Asselian, the platform became more differentiated. Isolated carbonate buildups dominated by *Palaeoaplysina* – phylloid algal material, and larger stacked buildup complexes dominated by bryozoans and submarine cement, developed (Elvebakk et al., 2002; Samuelsberg et al., 2003). The carbonate production was high, and several authors (e.g. Colpaert et al., 2007; Rafaelsen et al., 2008) have suggested a gradual change from a distally steepening ramp prograding into deeper water, to a more protected shelf and basin separated by a steeper slope, associated with higher subsidence rates in the Nordkapp Basin.

The high-frequency and high-amplitude glacioeustatic sea level fluctuations resulted in repeated exposure of the carbonate platform (Larssen et al., 2002). During lowstands, restricted connection between the central shelf and the northern ocean resulted in evaporite-filled sub-basins (Figure 5D) (Stemmerik and Worsley, 2005).

A flooding event that records a major shift in depositional conditions on the northern Pangean shelf occurred in the early Sakmarian. Deposition of the cyclic, often exposure-capped carbonate successions on the platform ceased, and deeper shelf deposits became dominant on the Finnmark Platform (Stemmerik and Worsley, 2005).

2.2.3 Bjarmeland Group

A subaerial exposure surface separates the lower Sakmarian warm-water carbonate succession from the overlying mid-Sakmarian to late Artinskian (lowermost Kungurian?) cool-water carbonates of the Bjarmeland Group (Larssen et al., 2002; Stemmerik and Worsley, 2005). The transition reflects a shift from a subtropical warm-water carbonate platform (Figure 5C) to a temperate cool-water carbonate platform (Figure 5E) (Samuelsberg et al., 2003; Stemmerik and Worsley, 2005) as a result of major re-organization of the central Pangean shelf (Stemmerik and Worsley, 2005). An abrupt depositional and architectural shift took place, and Stemmerik and Worsley (2005) suggest that it was a consequence of changing oceanographic circulation associated with changing tectonic configurations, likely related to development of the Uralides. The water depth and temperature was radically changed (Worsley, 2008).

The climate shift also affected the fauna; the diverse photozoan assemblages observed in the Gipsdalen Group were replaced by less diverse heterozoan biota in the Bjarmeland Group (Colpaert et al., 2007). Bryozoans, brachiopods, echinoderms and siliceous sponge spicules dominate this colder-water biotic association. Calcite precipitation is abundant, and there is little evidence of submarine cementation (Beauchamp and Desrochers, 1997).

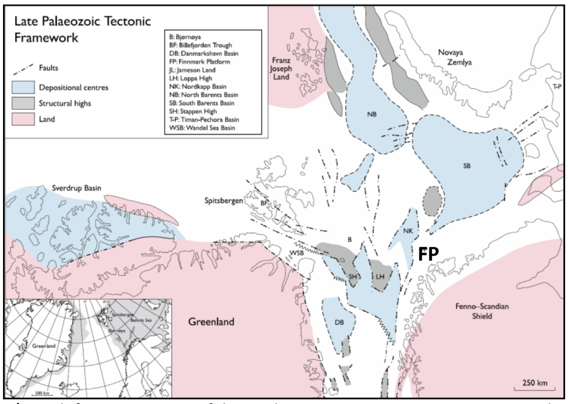
A major transgression took place during the mid-Artinskian. A heterozoan carbonate factory was installed, and in late Artinskian time, the central Pangean shelf, including the Finnmark Platform, was part of an extensive cool-water carbonate shelf that could be traced all the way to the Sverdrup Basin in the Arctic Canada (Figure 5E) (Stemmerik and Worsley, 2005). Development of carbonate mounds and ridges, dominated by bryozoan-*Tubiphytes* grainstones and cementstones with *Stromatactis* fabrics, took place.

2.2.4 Tempelfjorden Group

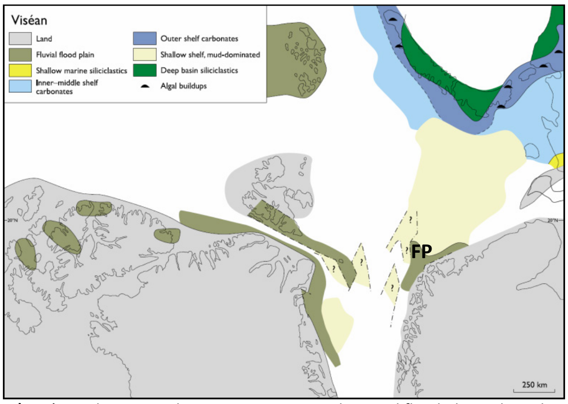
The Barents Sea region was subjected to a major drowning event during the Kungurian time (Stemmerik and Worsley, 2005), simultaneously as there was an ongoing transition toward cooler climatic conditions (Figure 5F) (Larssen et al., 2002). The cool-water carbonates within the Bjarmeland Group were overlain by the spiculitic-chert dominated Tempelfjorden Group (Rafaelsen et al., 2008). Palynological data from cores taken updip on the Finnmark Platform, has indicated a Kungurian to Kazanian age for the group (Larssen et al., 2002).

The sudden change in lithofacies that has been observed between the Bjarmeland Group and the Tempelfjorden Group indicates rapid transgression and flooding of the Finnmark Platform (Colpaert et al., 2007). The change from heterozoan biota to spiculites is indicative of major cooling of the ocean waters, associated with a major change in ocean circulation (Beauchamp and Baud, 2002). The Uralian orogeny was encroaching at the time, and closure of the Uralian seaway to the tropical regions of the peri-Caspian basin, has been suggested as a likely cause for this major cooling event (Colpaert et al., 2007). The real carbonate platform development ceased in the late Artinskian, but biogenic production was still important during the Kungurian times, as spiculitic chert and shales dominated the lithofacies (Colpaert et al., 2007). Silica and low-Mg calcite are the main mineralogical species in these sediments (Beauchamp and Desrochers, 1997).

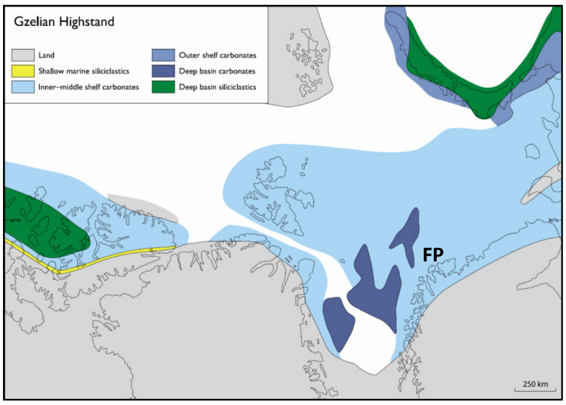
During the latest Permian a renewed transgression occurred, which terminated the period of important biogenic production and sedimentation across the Finnmark Platform (Colpaert et al., 2007). The climate became progressively colder, and the sedimentation became gradually more siliciclastic dominated (Samuelsberg et al., 2003). The Triassic was characterized by massive clastic influx onto the platform (Colpaert et al., 2007).



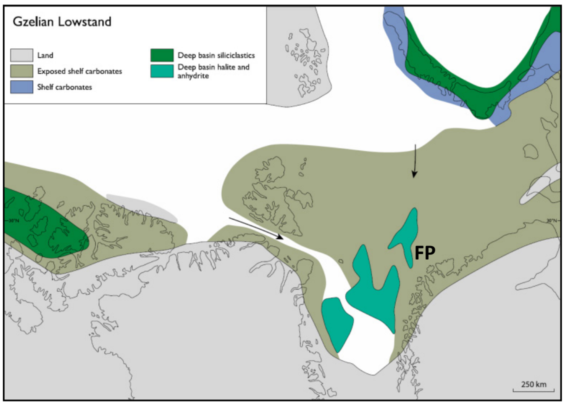
A) Pre-drift reconstruction of the northern Pangean margin. Major structural elements are shown. The present day positions of Greenland and Norway and adjacent shelf areas are shown in the inset map.



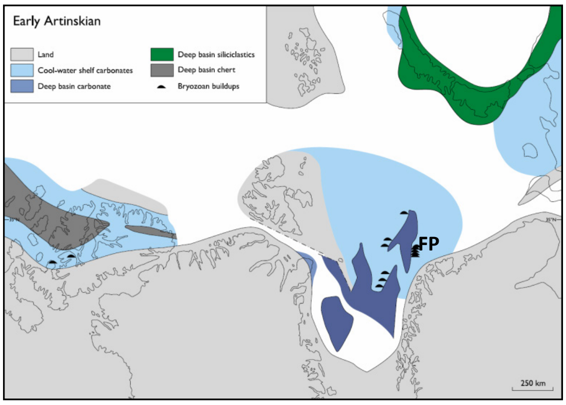
B) Viséan paleogeographic reconstruction. Widespread flood plains along the southern shelf margin. Warm and humid conditions dominated.



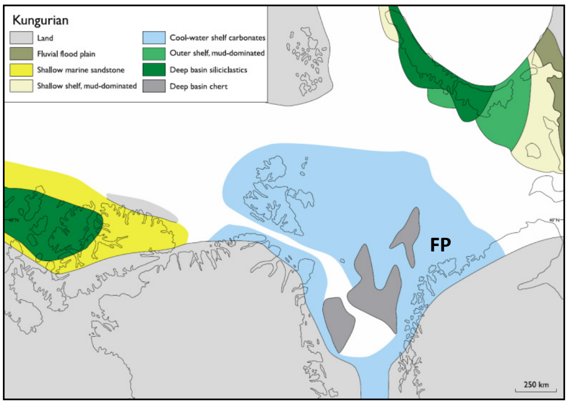
C) Widespread warm water carbonate depostiion during Gzelian highstands.



D) Temporary subaerial exposure of huge shelf areas during Gzelian lowstands. The marine connection to the deep basins on the central shelf was restricted; arrows indicate possible connection.



E) Cool-temperate conditions and widespread cool-water carbonate sedimentation during Early Artinskian.



F) Kungurian cool-cold temperate conditions.

Figure 5: A) Pre-drift reconstruction of the northern Pangean margin. B) - F) Paleogeographic reconstructions of the northern Pangean shelf during the Late Paleozoic. FP= Finnmark Platform. Modified from Stemmerik and Worsley (2005).

Chapter 3: Methodology and data

In this study, interpretation of 2D and 3D seismic data have been combined with information from five exploration wells and eight shallow cores (Figure 2). Landmark DecisionSpace® software provided by Halliburton was used for interpretation of both the well and seismic data.

3.1 Wells

A total of five exploration wells have penetrated the Upper Paleozoic succession on the Finnmark Platform. Consequently, these five wells have been incorporated in this study (Table 1, Figure 2). Only one of the wells is located on the western part of the platform, whereas the other four are penetrating eastern parts of the platform (Figure 2). Well 7128/6-1, located on the eastern Finnmark Platform (Figure 2), cored more than 400 meters of the Upper Paleozoic succession (Ehrenberg et al., 1998), thus providing essential stratigraphic and lithological information about the interval. Information from published core data and well logs (e.g. from Bugge et al., 1995; Ehrenberg et al., 1998; Ehrenberg et al., 2000; Larssen et al., 2002), in addition to geochemical and final well reports (e.g. available from Norwegian Petroleum Directorate's factpages), for the five exploration wells, were found useful and hence incorporated in this study. The widely spaced wells (Figure 2) lead to relatively poor well control in the study area. Despite this, the wells were used for the best possible correlation of seismic stratigraphic sequences. Stacking patterns were analyzed in order to identify main surfaces, including maximum flooding surfaces and unconformities. These were further combined with official formation tops from the Norwegian Petroleum Directorate (NPD), and formed the basis for well correlations.

In addition to the exploration wells, IKU (now SINTEF) Petroleum Research drilled eight shallow cores on the Finnmark Platform (Table 1, Figure 2) during the latter half of the 1980s (Larssen et al., 2002). These shallow cores encountered various parts of the Upper Paleozoic succession (Table 1). Published information regarding these shallow cores (e.g. from Bugge et al., 1995; Ehrenberg et al., 2000; Larssen et al., 2002) formed the basis, and allowed for, their incorporation as part of the dataset for this project.

3.2 Seismic

In order to define depositional sequences with characteristic seismic signatures, regional 2D seismic data was supplemented with more localized 3D seismic data. Seismic data allows us to extrapolate point source information from wells and is therefore important when investigating the platform geometry and its carbonate buildup development. The seismic data was obtained from Disko's PetroBank, provided by Halliburton Norge, and covers the entire Finnmark Platform (Figure 2).

Three 3D surveys were incorporated in this study. SH9102 and ST9802 enclose nearly 600 km^2 and 1900 km^2 respectively, and are located on the eastern part of the platform (Figure 2), while EN0702 covers almost 1800 km^2 and is located on the central part of the platform (Figure 2). The dominant frequencies for the interval of interest vary between the different 3D surveys, although overall appearing in the range from 12 Hz to 35 Hz. More specified information about the dominant frequencies for the different surveys is presented in Table 2.

There is extensive coverage of 2D lines on the Finnmark Platform. The 2D lines cover the entire platform (Figure 2), with an area of approximately 40 000 km^2. The 2D lines were interpreted to obtain a more regional perspective, and they were also used to tie the different 3D cubes. The 2D seismic data appears to be close to zero phase, and an increase in acoustic impedance is represented by a peak. The various 2D lines originate from different surveys, and have hence various frequencies. For the interval of interest, the frequencies are predominantly in the range from 10 Hz to 45 Hz.

The interval velocities of the Upper Paleozoic succession range from 2900 m/s to 6900 m/s, although predominantly occurring between 5000 m/s and 6000 m/s (see Table 3). The complexity of carbonate facies leads to heterogeneities at all scales and should be taken into consideration when interpreting seismic signals of carbonate successions. Artefacts such as pull-up effects are easily created as a result of abrupt lateral velocity changes. The observed dominating frequencies for the 3D surveys (Table 2) and the predominant interval velocities for the interval of interest (Table 3), result in a vertical resolution of approximately 45-50 meters in the Upper Paleozoic carbonate succession.

Overall, four seismic units were defined based on laterally extensive seismic reflectors that were correlative with observed stacking patterns from the wells. Wells 7128/4-1and 7128/6-1, and the seismic appearance on the 2D lines in the adjacent area, were chosen as the main basis for definition of the seismic units, as the Upper Paleozoic interval has been penetrated and extensively cored in these wells. Hence, they represent good stratigraphic control points. Terminations such as toplap, downlap, and/or onlap were often associated with the boundaries separating the seismic units. Acoustic impedance contrasts, and thus also distinct seismic events, are often a result of stratigraphic lithology variations (evaporites, dolomites, limestones, siliciclastics and spiculitic chert) and/or porosity variations. This has been confirmed as the seismic sequences are shown to be closely related to three of the well-known Upper Paleozoic depositional sequences; the Gipsdalen Group, the Bjarmeland Group and the Tempelfjorden Group.

3.2.1 Seismic-well tie

In order to constrain the age of the various seismic reflectors, synthetic seismograms were generated for the five exploration wells. Due to incorporation of various seismic surveys, with different frequencies and polarities, a zero-phase Ricker wavelet with a frequency of 20 Hz (Figure 6) was used to generate the synthetic seismograms. In order to compile a high-quality seismic analysis, high correlation coefficients between the seismic and synthetics are essential. Correlation coefficients and other synthetic correlation parameters for the five exploration wells are listed in Table 4.

Table 1: Information about exploration wells and shallow cores that are incorporated in this study.

Well	Operator	Total depth (m)	Oldest penetrated age	Current status
7128/4-1	Statoil	2530	Pre-Devonian	P&A OIL/GAS
7128/6-1	Conoco	2543	Pre-Devonian	P&A OIL SHOWS
7120/12-4	Norsk Hydro	2199	Late Carboniferous	P&A DRY
7228/9-1 S	Norsk Hydro	4600	Early Permian	P&A OIL/GAS SHOWS
7229/11-1	Shell	4630	Late Carboniferous	P&A DRY
7029/03-U-01	IKU	164.6	Early Carboniferous	
7029/03-U-02	IKU	201	Late Carboniferous	
7127/10-U-02	IKU	200.2	Early Carboniferous	
7127/10-U-03	IKU	153	Early Carboniferous	
7030/03-U-01	IKU	173.7	Late Carboniferous	
7128/12-U-01	IKU	160.2	Early Permian	
7129/10-U-01	IKU	93.3	Early Permian	
7129/10-U-02	IKU	119.9	Early Permian	

Table 2: Information about the dominant frequencies for the different 3D surveys incorporated in this study.

3D Survey	Year of acquirement	Dominant frequencies for the interval of interest
SH9102	1991	12-22 Hz
ST9802	1998	35 Hz
EN0702	2007	25 Hz

Table 3: Average, minimum, and maximum interval velocities within the Upper Paleozoic carbonate succession.

Well	Average interval velocity (m/s)	Minimum interval velocity (m/s)	Maximum interval velocity (m/s)
7120/12-4	4180	3369	5512
7128/4-1	4867	2936	5782
7128/6-1	4967	3730	6554
7229/11-1	6222	4694	6922
7228/9-1 S	5219	3272	6476

Table 4: Synthetic correlation parameters.

Well	Trace location survey/line	Phase rotation (deg)	Correlation coefficient between seismic and synthetic
7120/12-4	BSS01/203	-88	0.60
7128/4-1	BSS01/301	-126	0.45
7128/6-1	CN92/209	-55	0.70
7229/11-1	SH9102 (3D)	177	0.55
7228/9-1 S	IS-CNB-01-AGC/101	0	0.82

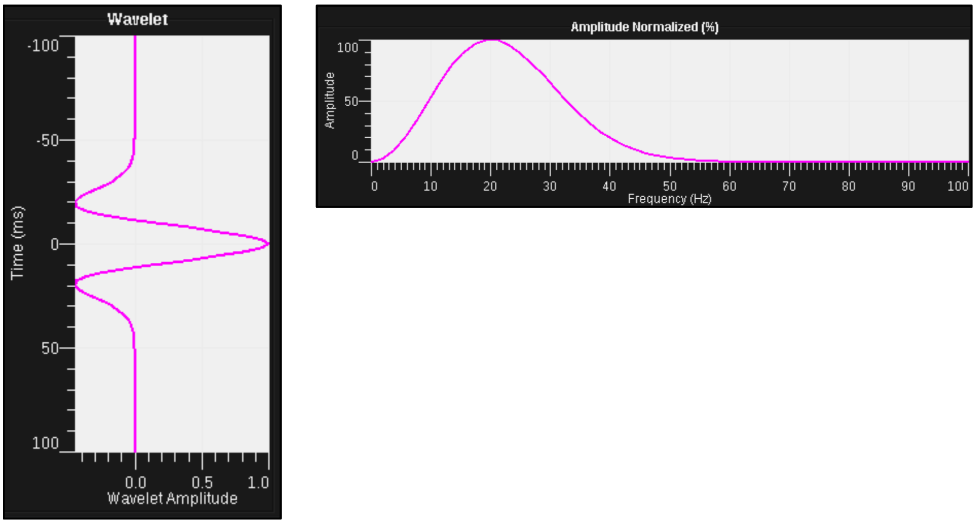


Figure 6: A zero-phase Ricker wavelet with a frequency of 20 Hz was used for generation of synthetic seismograms.

Chapter 4: Observations

Throughout this study, the formal lithostratigraphic scheme of the Upper Paleozoic succession proposed by Larssen et al. (2002) has been applied. Their nomenclature is well established and generally broadly accepted in the geological literature.

4.1 Regional observations

A regional well correlation (Figure 7), a lithostratigraphic column correlated with a characteristic well for the eastern (7128/6-1) and the western (7120/12-4) part of the platform (Figure 8), regional seismic lines (Figures 9 and 10), and a time thickness map of the Carboniferous-Permian biogenic interval (Figure 11), all reveal significant differences, both structurally and stratigraphically, across the study area. Based on this, three provinces could be defined; eastern, central and western Finnmark Platform.

4.1.1 Eastern province

Presence of four exploration wells, results in relatively good well control in the eastern province (Figure 2). Overall, these four wells (7128/4-1, 7128/6-1, 7229/11-1, 7228/9-1S) reveal similar log characteristics, including sections of “blocky” gamma-ray signature (Figures 7 and 8), characteristic of carbonates. Wells 7128/4-1 and 7128/6-1 are located only 26 km away from each other and their well characteristics appear to be of high similarity (Figure 7). This is also the case for wells 7229/11-1 and 7228/9-1 S, which are separated by 38 km (Figure 7).

For the wells on the proximal part of the eastern platform, wells 7128/4-1 and 7128/6-1 (Figure 2), the Upper Paleozoic interval has been penetrated and cored in its entirety. Consequently, all of the four seismic units (SU1-SU4), which appear to have a close relationship to the Late Carboniferous-Permian depositional sequences (Figure 8), could be identified in these wells (Figures 7 and 8). Only minor thickness variations of the units can be observed between wells 7128/4-1 and 7128/6-1 (Figure 7).

For the wells on the distal part of the eastern platform, wells 7229/11-1 and 7228/9-1S (Figure 2), only the uppermost part of the Upper Paleozoic interval has been penetrated. Consequently, signatures of only three of the seismic units (SU2-SU4) can be identified in these wells (Figure 7). However, the seismic data in the area indicates that the fourth unit (SU1) is also present, although being located on greater depths than the total depth of the wells (Figure 10). A minor increase in thickness of the units can be seen in the most distal well 7228/9-1S, in comparison to well 7229/11-1 (Figure 7).

The regional well correlation (Figure 7) shows that the Upper Paleozoic succession was encountered at shallower depths (at approximately 1600 meters) on the proximal platform, compared to on the more distal part of the platform (near 4000 meters depth). In addition, an overall distal increase in the thickness of the units can be observed (Figure 7). However, this excludes seismic unit 4 (SU4), which appears thinner in the distal wells of the platform (Figure 7).

The regional seismic lines (Figures 9 and 10) show the presence of the four seismic units (SU1-SU4) in the eastern province. The seismic units appear thinner over structural highs, and support the distal increase in thickness (Figures 9 and 10) as observed from the wells (Figure 7). Overall, the Upper Paleozoic succession does not appear significantly affected by neither syn-depositional nor post-depositional fault activity (Figures 9 and 10). However, evidence of pre-depositional, and possibly also minor early syn-depositional fault activity can be observed, predominantly affecting the underlying basement configuration (Figures 9 and 10). Figure 10 shows a composite line going from south to north on the eastern part of the platform. Overall, the interval of interest is characterized by semi-horizontal reflections in the south. Towards the north, the interval becomes characterized by more inclined reflections, as the seismic units are progressively located on greater depths. Several structural highs and mounded features are present.

The time thickness map of the Carboniferous – Permian biogenic interval shown in Figure 11, also reveals an overall distal increase in thickness. On the inner platform areas the interval appears with a thickness in the range of 100-200 ms TWT, whilst it on the outer platform areas reaches a thickness of approximately 500 ms TWT.

4.1.2 Central province

No wells have been drilled in the central province. The regional seismic line (Figure 9) shows that the central province is represented by a highly deformed area located on shallower depths. Several of the seismic units identified in the eastern province, seem to pinch-out near this highly deformed area (Figure 9). The observed decreased thickness of several of the seismic units is also supported by the time thickness map of the entire interval (Figure 11), which shows that the overall thickness is predominantly less than 100 ms TWT in this province. This is clearly the part of the study area where the Carboniferous-Permian biogenic interval appears thinnest (Figure 11).

4.1.3 Western province

Presence of only one exploration well (7120/12-4), results in poor well control in the western province (Figure 2). Overall, the gamma-ray characteristics of this well reveal dominance of clastic sediments, clearly contrasting the “blocky” gamma-ray signature of the wells in the eastern province (Figures 7 and 8). Strata from only two (SU1 and SU4) of the four defined seismic units were encountered in the west, and in addition, the gamma-ray signatures of these two seismic units appear different compared to in the east (Figures 7 and 8). Only a few of the Late Carboniferous – Permian depositional sequences (the Gipsdalen Group and the Tempelfjorden Group) were penetrated in the western province (Figure 8), and this, combined with the regional well correlation (Figure 7), indicates that during the Late Paleozoic, significant differences in sedimentation patterns occurred across the Finnmark Platform.

The western province is characterized by thicker and fewer well and seismic units, compared to the central and eastern provinces (Figures 7, 8 and 9). In addition, in the western province the Upper Paleozoic succession appears more affected by syn- and post-depositional faulting (Figure 9). Overall, the western province appears as a structurally complex area, with corresponding high thickness variations of the Upper Paleozoic biogenic interval (Figure 11).

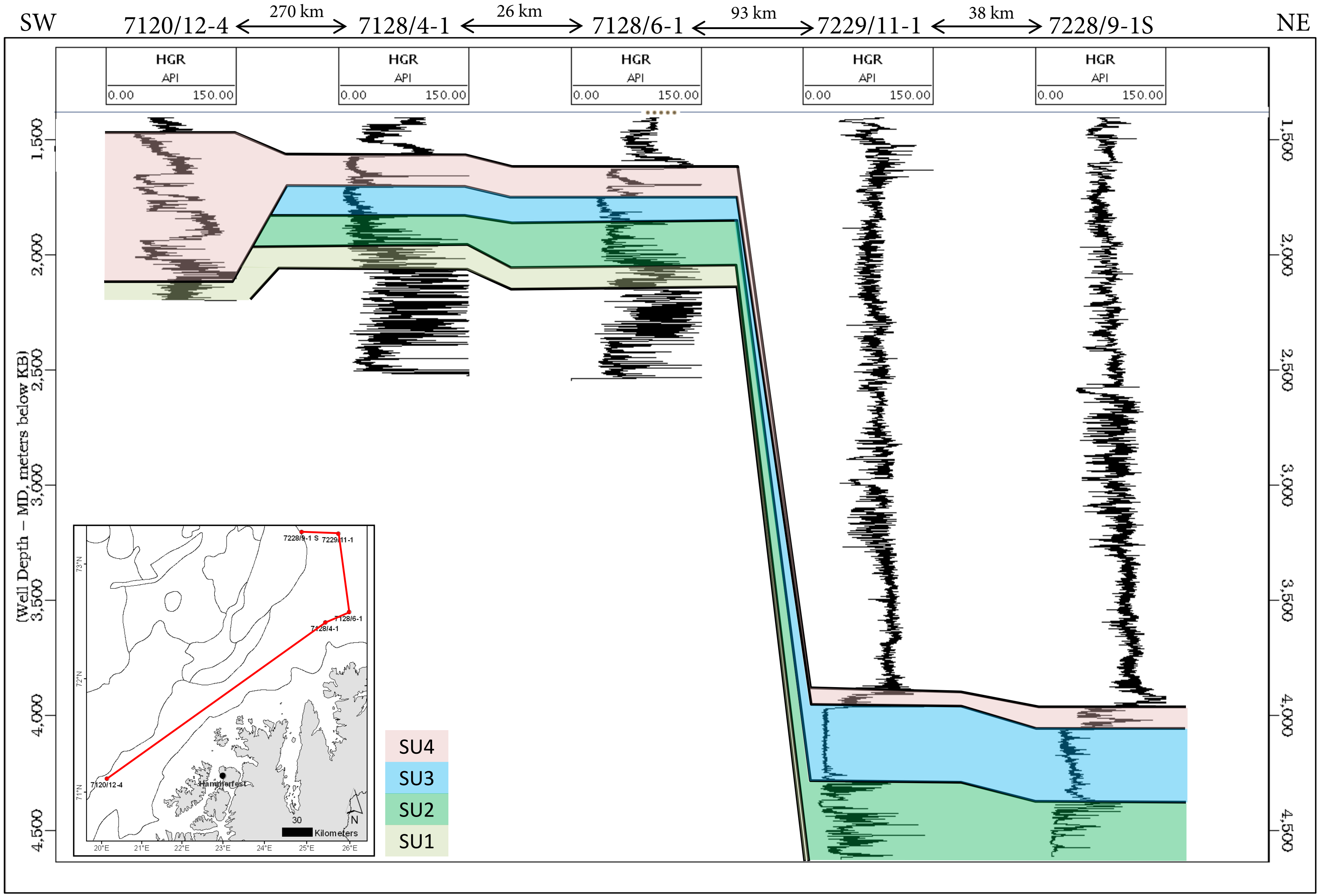


Figure 7: Regional well correlation across the study area. The inset map shows the correlation path. Note the different gamma-ray signature of the western well (7120/12-4) compared to the eastern wells (7128/4-1, 7128/6-1, 7229/11-1, 7228/9-1S). Overall, the gamma-ray characteristic of the western well reveals dominance of clastic sediments, whereas the eastern wells have a more “blocky” gamma-ray signature, characteristic of carbonates.

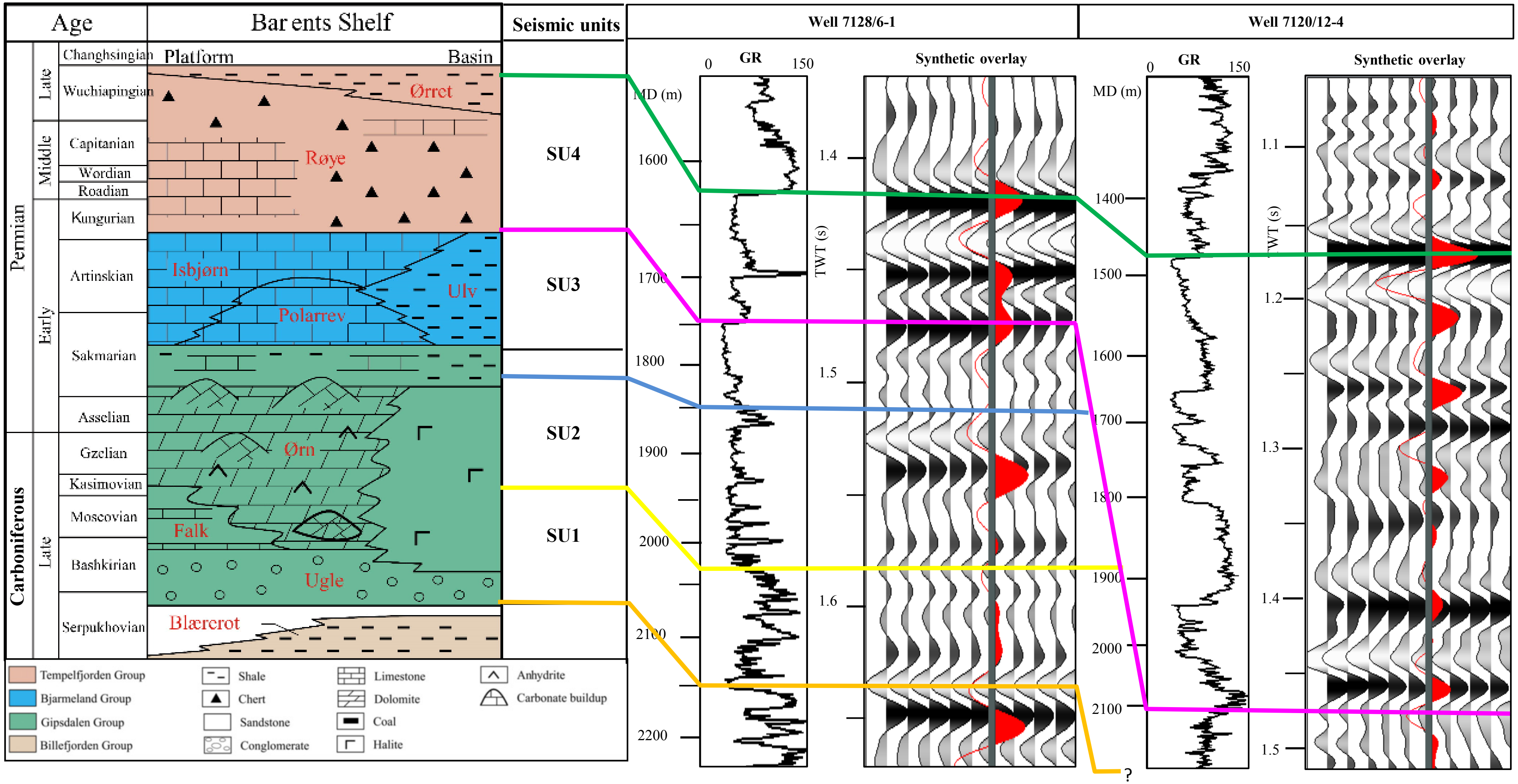
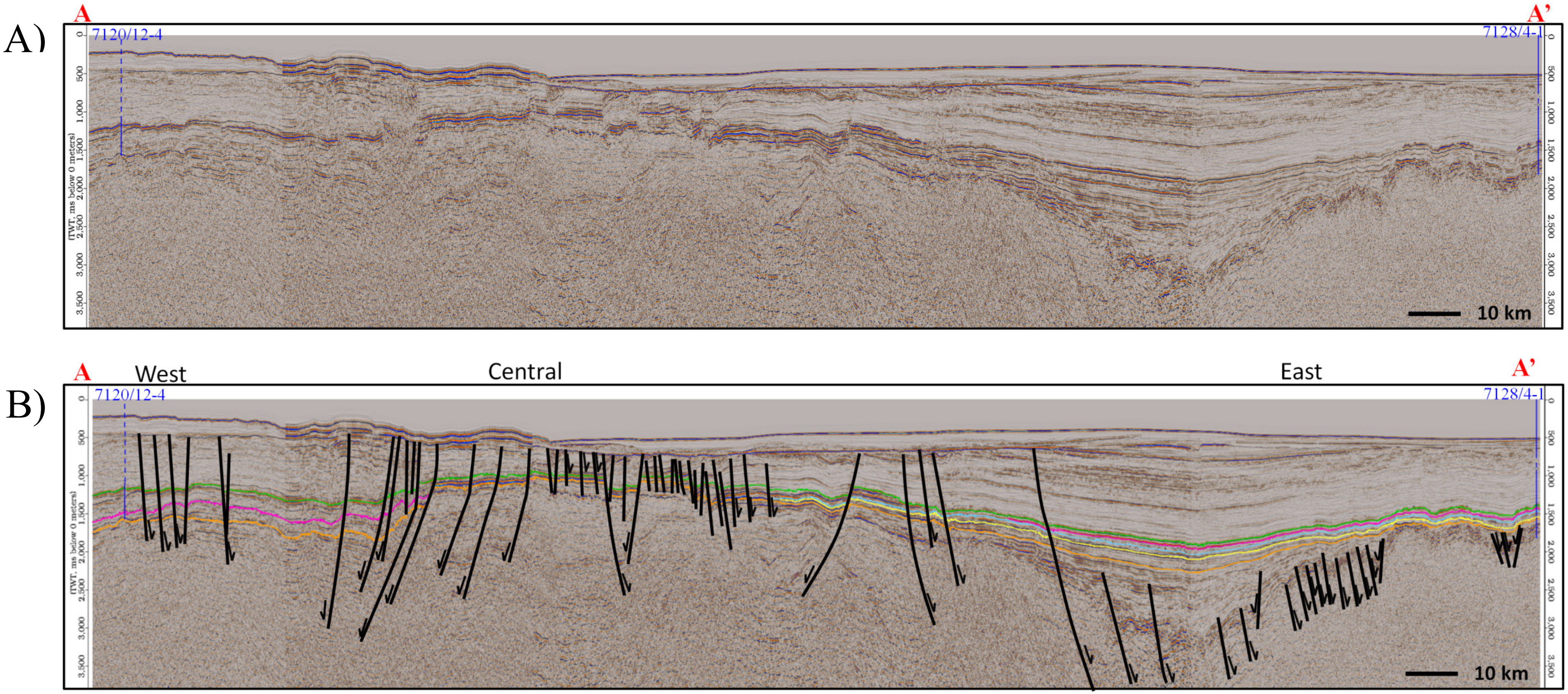


Figure 8: Lithostratigraphic column (modified from Rafaelsen et al., 2008) correlated with synthetic and gamma-ray of a characteristic well for the eastern (7128/6-1) and the western (7120/12-4) Finnmark Platform.



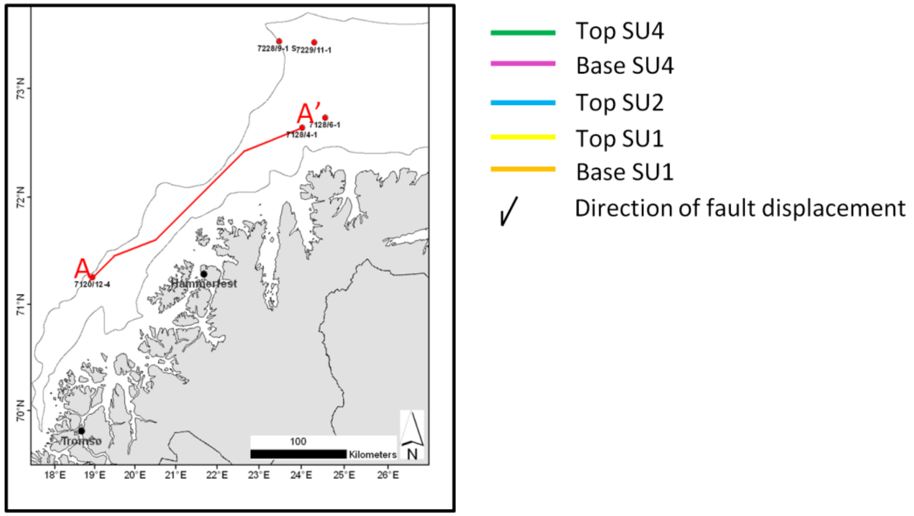
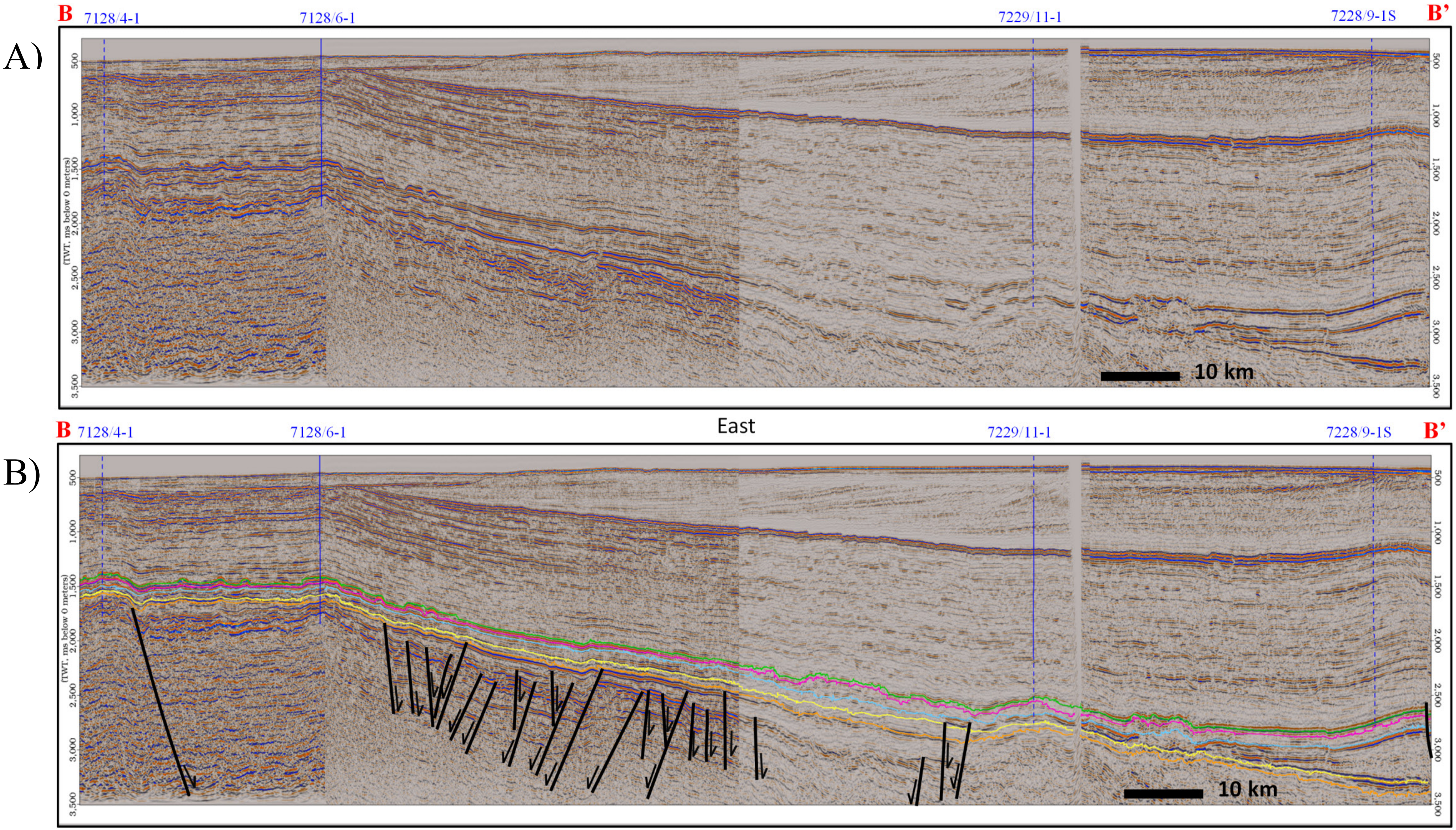


Figure 9: A) Uninterpreted and B) interpreted regional composite seismic line across the study area. The location of the line is shown on the map in the lower left corner. Three provinces; west, central, and east, can be defined based on differences in structural and stratigraphic appearance.



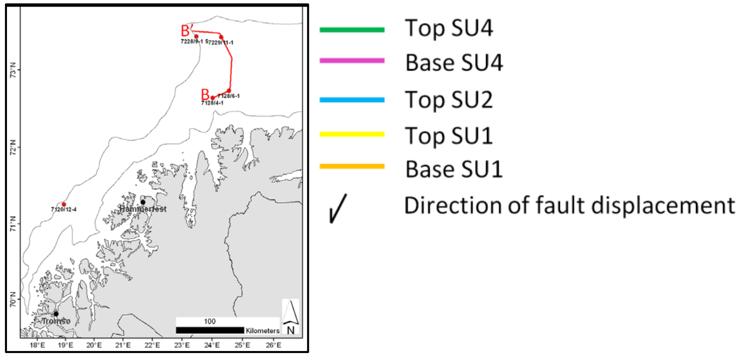


Figure 10: A) Uninterpreted and B) interpreted regional composite seismic line over the eastern part of the study area. The location of the line is shown on the map in the lower left corner. The eastern province seems to have represented a stable platform since the Late Paleozoic times. No post-depositional, and only minor syn-depositional fault activity can be observed.

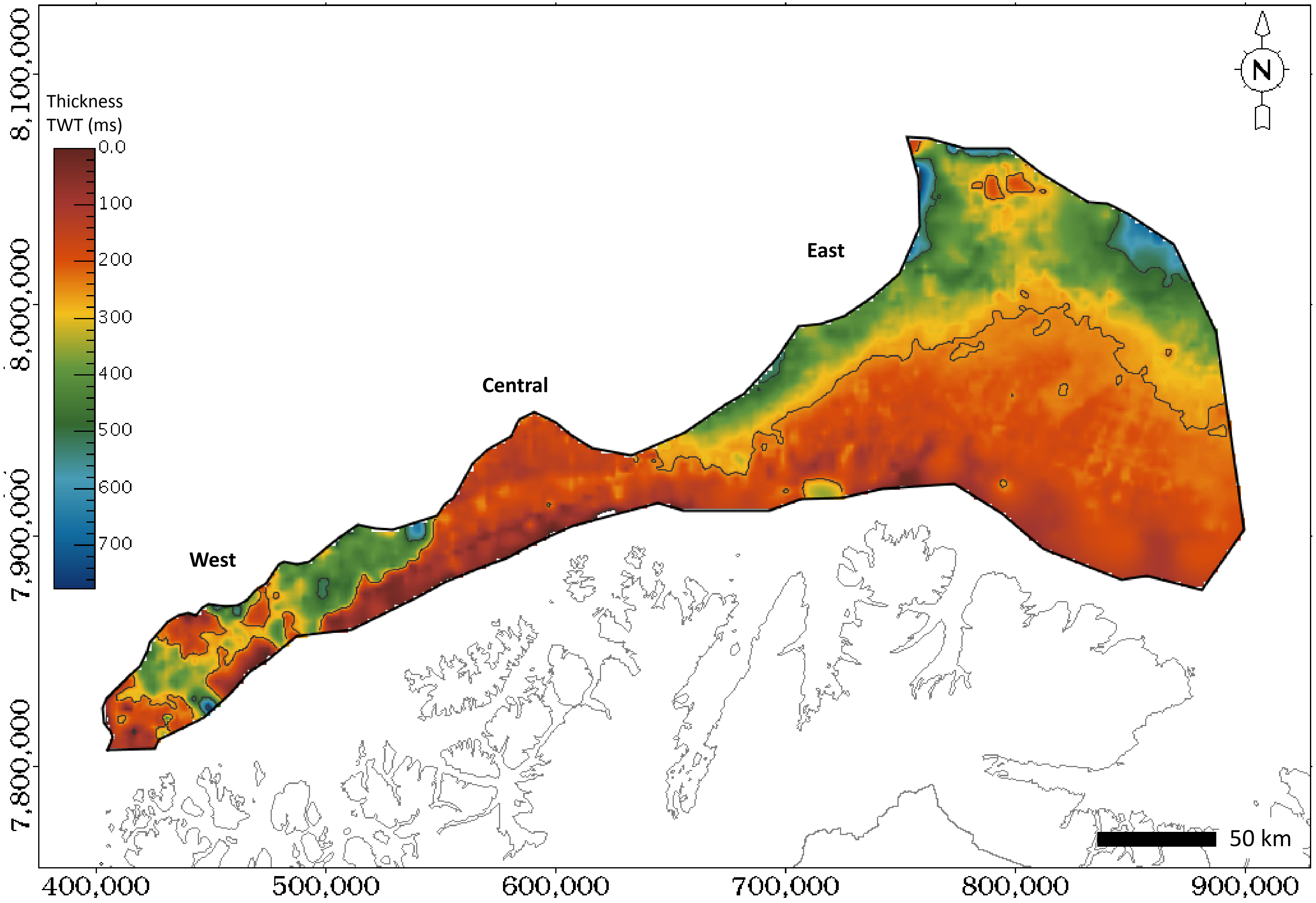


Figure 11: Time thickness map of the Carboniferous - Permian biogenic interval on the Finnmark Platform. Note the distal increase in thickness in the east, overall low thickness in the central, and varying thickness in the west. Coordinate system UTM 34 ED 50.

4.2 Structural Framework

Through time, large parts of the Finnmark Platform have clearly been affected by several phases of deformation. The structural interpretation led to identification of four main fault families in the study area. The occurrence of the observed fault families, in relation to the three provinces, is shown in Figures 12 and 13. It should be mentioned that only the main faults have been interpreted and correlated, given the time frame and the main stratigraphical focus of this study. A description, combined with examples, of the different fault families will now follow. The location of the seismic lines referred to within this section is shown in Figure 14.

4.2.1 FF1

Fault family 1 (FF1) represents a cluster of NNE-SSW striking normal faults, which dominate the southwesternmost part (western province) (Figure 12) of the Finnmark Platform. The dip of the faults seems to decrease with depth (Figures 15 and 16), and FF1 is hence interpreted as being of a listric character. The concave part is facing the northwestern-lying Harstad basin. A major bounding fault stretching from 70°33’N to 70°58’N (Figure 12) serves as a structural division between the Finnmark Platform and the Harstad Basin. In addition, another major bounding fault is observed further to the north (71°13’N - 71°47’N) (Figure 12), partly separating the Finnmark Platform from the Hammerfest Basin. The northernmost bounding fault serves as a structural division between the western and central provinces of the Finnmark Platform (Figures 12 and 13), and is associated with significant increase in thickness of the Upper Paleozoic succession (Figure 11). Thickness variations across some of the faults assigned to FF1, especially those present on the inner part of the platform (Figures 15 and 16), indicate that they were active in the end of Permian.

4.2.2 FF2

Fault family 2 (FF2) represents a set of NE-SW striking normal faults, which have been observed in all the three provinces of the study area (Figure 12). These faults have been observed dipping both basinwards and landwards, although a predominant trend of dipping basinwards has been observed (Figures 12 and 13). The faults assigned to FF2 seem to segment the platform into NE-SW oriented terraces (Figures 12 and 13). Major bounding faults with listric geometries separate the Finnmark Platform from the Hammerfest Basin (Figures 16 and 17), in addition to be present more on the inner parts of the platform (Figures 16, 17, 18 and 19). Although the faults assigned to FF2 affect the Upper Paleozoic succession, no evidences of activity at the time of deposition have been observed. The thickness across the faults of FF2 appears constant (Figures 16, 17 and 18). However, an overall decrease in the thickness of the Upper Paleozoic succession is observed from the outer towards the inner parts of the platform (Figures 17, 18 and 19). This decrease in overall thickness is thought to be related to the geometry of the platform, rather than being fault controlled. The faults of FF2 appear to have been active post-deposition of the Upper Paleozoic interval, and several of the major faults have indications of being reactivated several times (Figures 16 and 17).

4.2.3 FF3

Fault family 3 (FF3) is represented by a localized WNW-ESE striking normal fault, which appears as a bounding platform fault on the central part of the platform (Figures 12 and 19). The concave part is oriented northwards, in direction of the Nordkapp Basin. On the central part of the platform, FF3 seems to interact with both FF1 and FF2 (Figure 12), however at this stage it is not clear how these fault systems are linked (not focus of study and needs further investigation).

4.2.4 FF4

Fault family 4 (FF4) comprises NE-SW striking (Figure 12) normal faults, without any indications of listric geometries. The faults of FF4 are basement involved and form rotated fault-blocks (Figure 20). Their appearances indicate predominant activity pre-deposition of the Upper Paleozoic succession (Figure 20). However, some indications of activity during the earliest stages of deposition of seismic unit 1 (SU1) have been made (Figure 20). The faults assigned to FF4 have only been observed in the eastern province of the platform where they are observed to dip towards the Norwegian mainland (Figures 12 and 13).

In addition to the faults assigned to FF4, there have been observed several faults affecting the basement on the eastern province of the platform. However, the combination of overall small displacements, reduced seismic quality, and likely pull-up effect caused by the overlying carbonates, resulted in challenging fault correlation on the eastern province. Indications of faults striking in a NW-SE direction have been observed, however the correlation attempt was eventually considered not being successful.

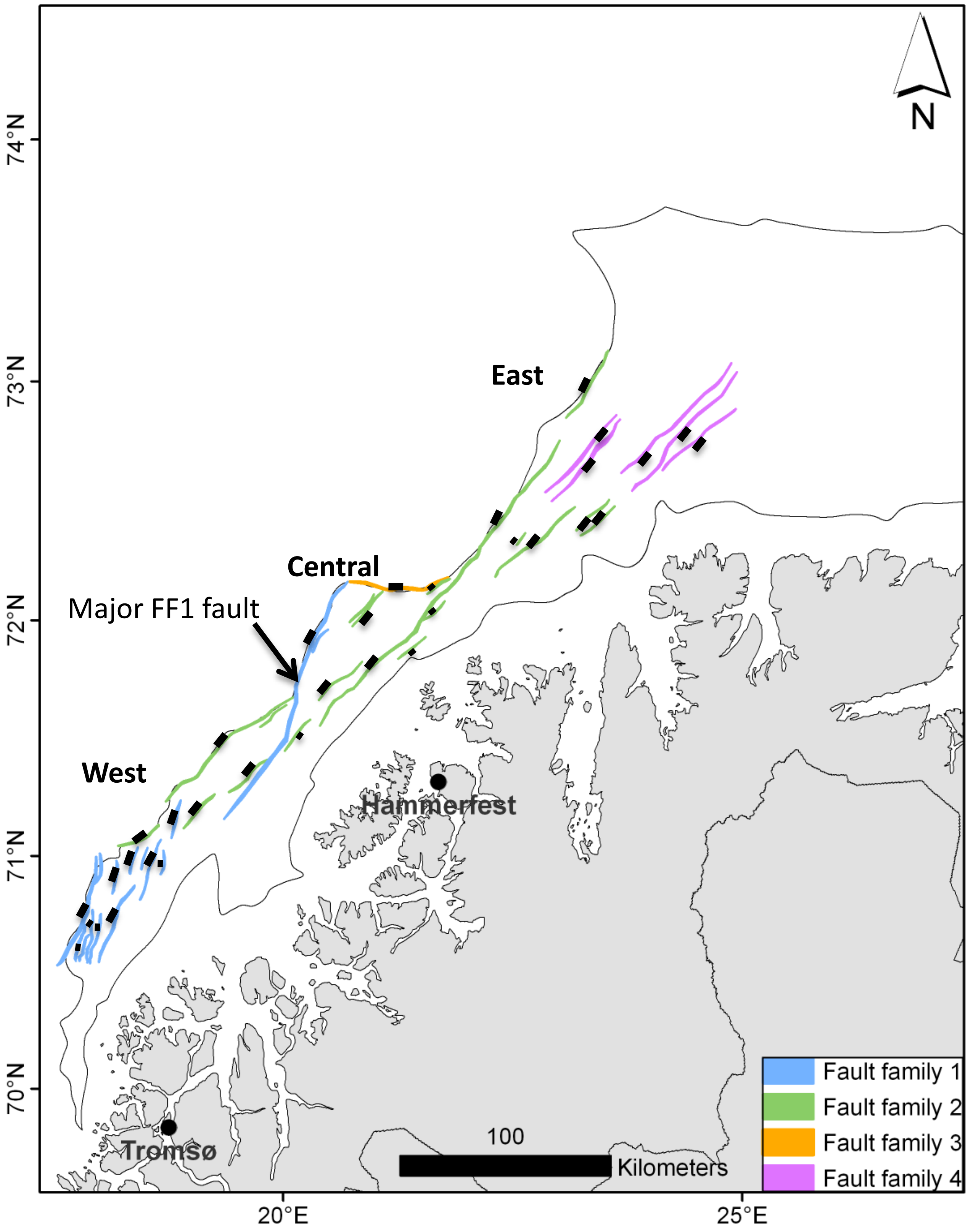


Figure 12: Observed fault families in relation to the three defined provinces. Fault family 1 (FF1) comprises NNE-SSW striking faults, which dominates the western province. A major FF1 fault separates the central and western provinces. NE-SW striking faults assigned to fault family 2 (FF2) have been observed in all of the three provinces, whereas a WNW-ESE striking fault assigned to fault family 3 (FF3) has been observed on the central platform. See text for more details.

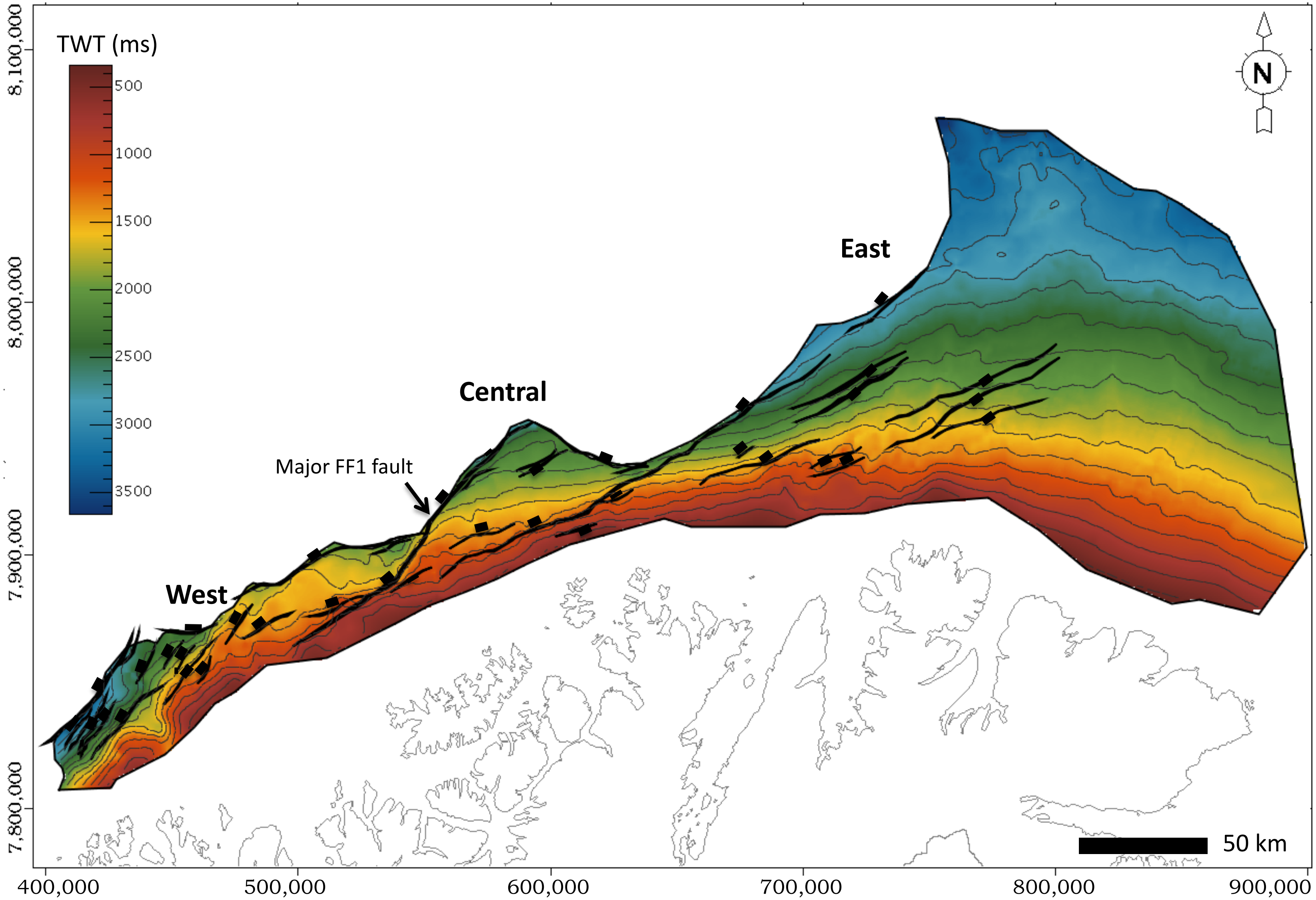


Figure 13: Time structure map of the base (Top Billefjorden horizon) of the Upper Paleozoic biogenic interval across the study area. A monocline platform geometry is revealed. Coordinate system UTM 34 ED. 50.

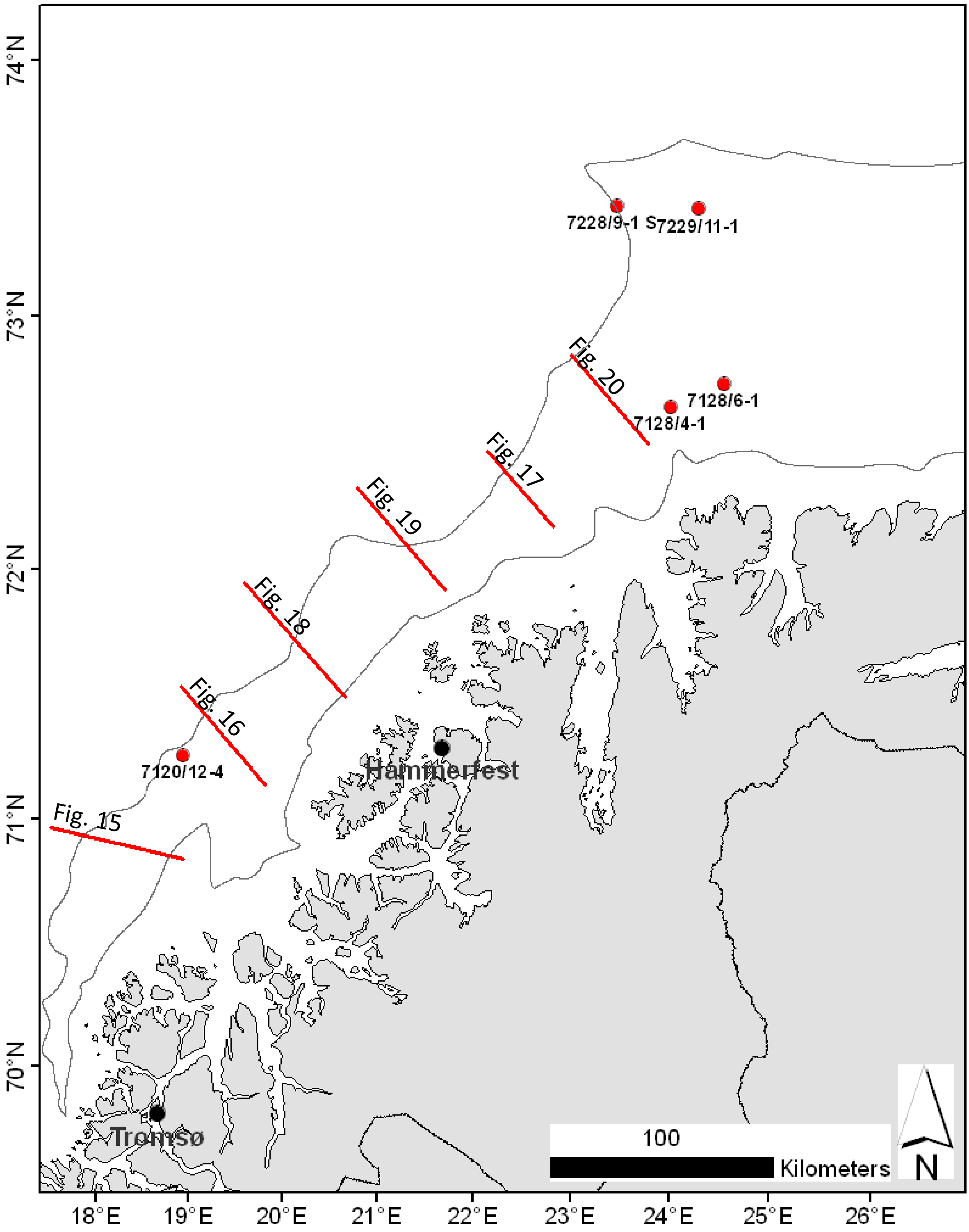


Figure 14: Locations of seismic lines referred to within the structural framework (section 4.2).

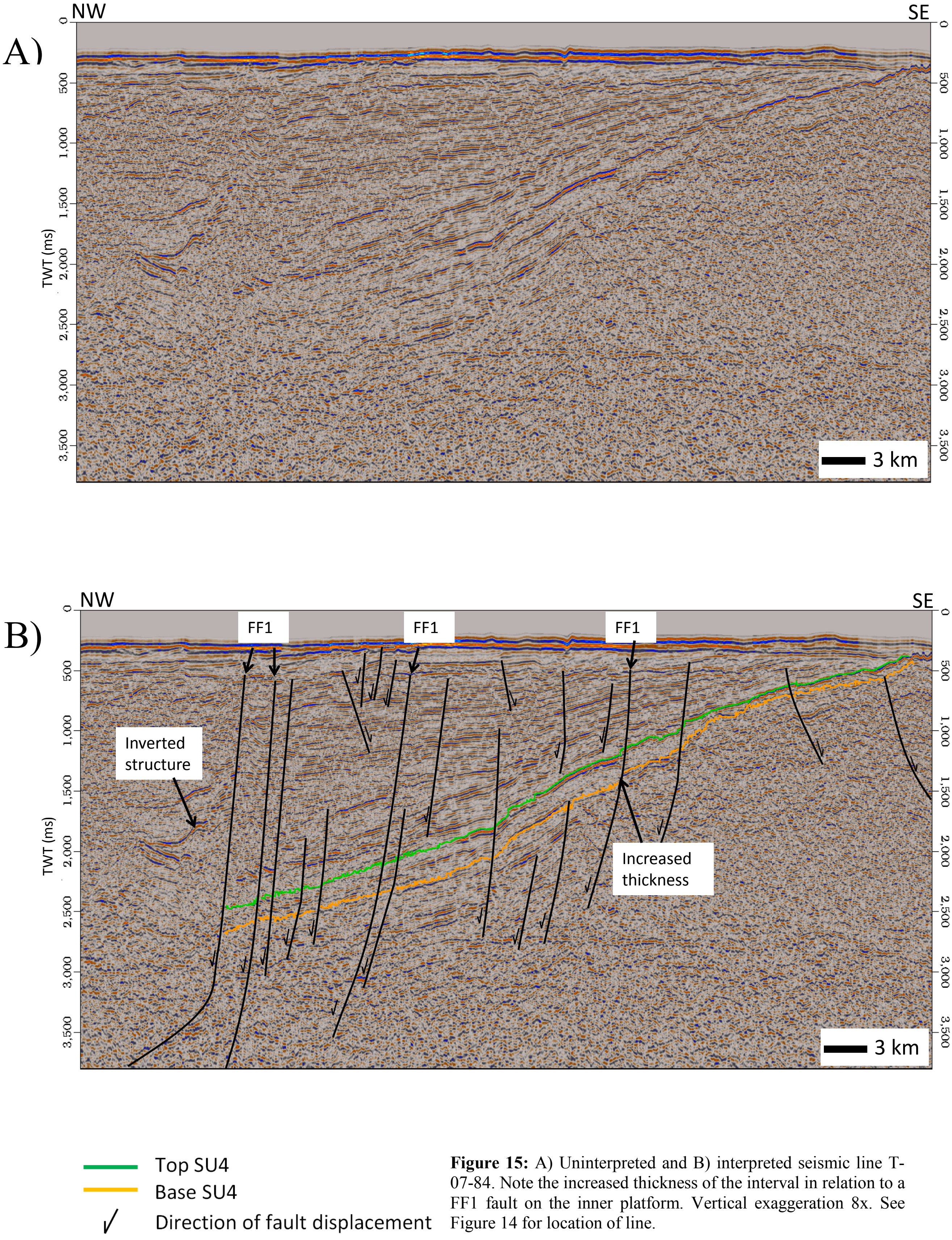


Figure 15: A) Uninterpreted and B) interpreted seismic line T-07-84. Note the increased thickness of the interval in relation to a FF1 fault on the inner platform. Vertical exaggeration 8x. See Figure 14 for location of line.

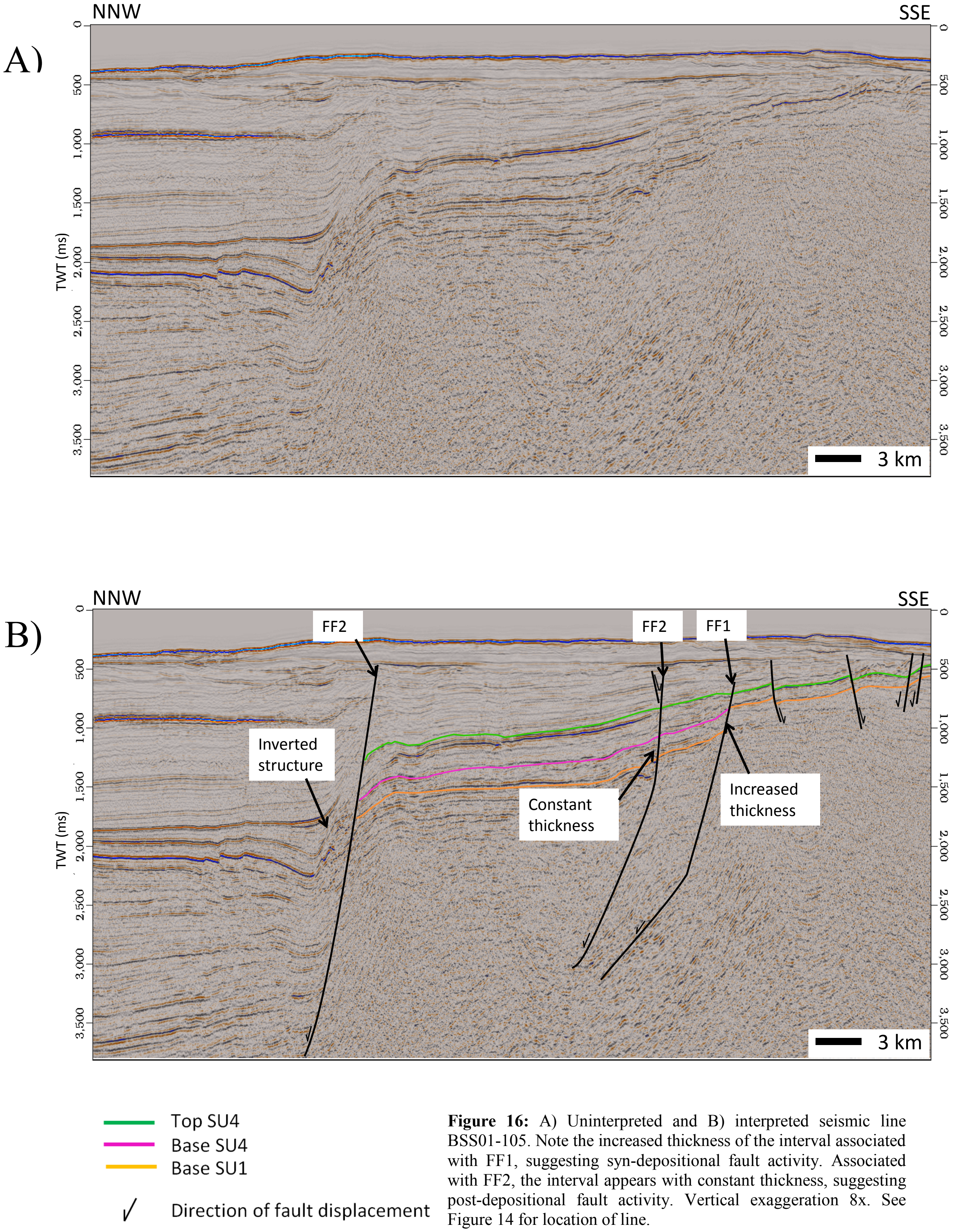


Figure 16: A) Uninterpreted and B) interpreted seismic line BSS01-105. Note the increased thickness of the interval associated with FF1, suggesting syn-depositional fault activity. Associated with FF2, the interval appears with constant thickness, suggesting post-depositional fault activity. Vertical exaggeration 8x. See Figure 14 for location of line.

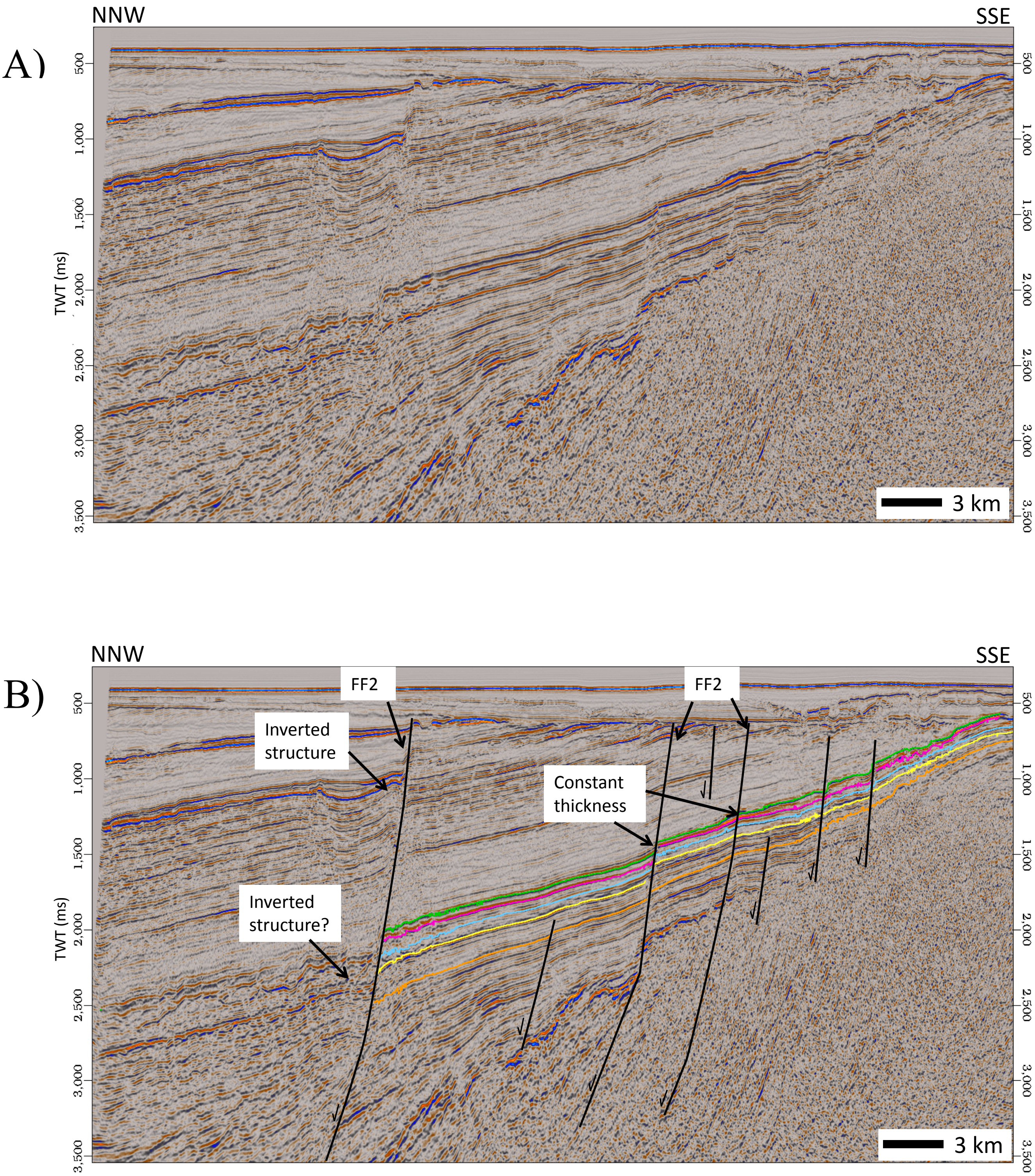
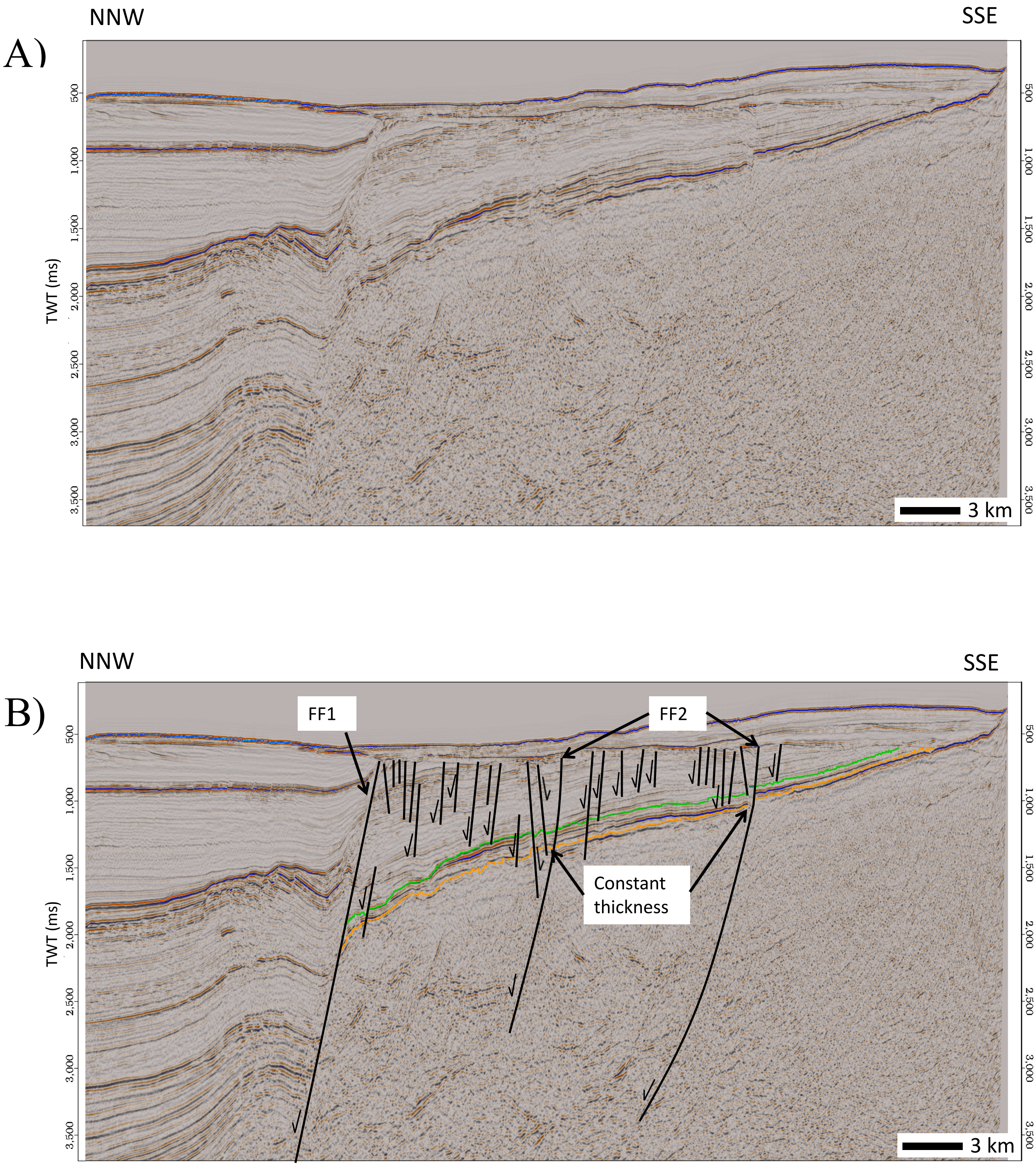
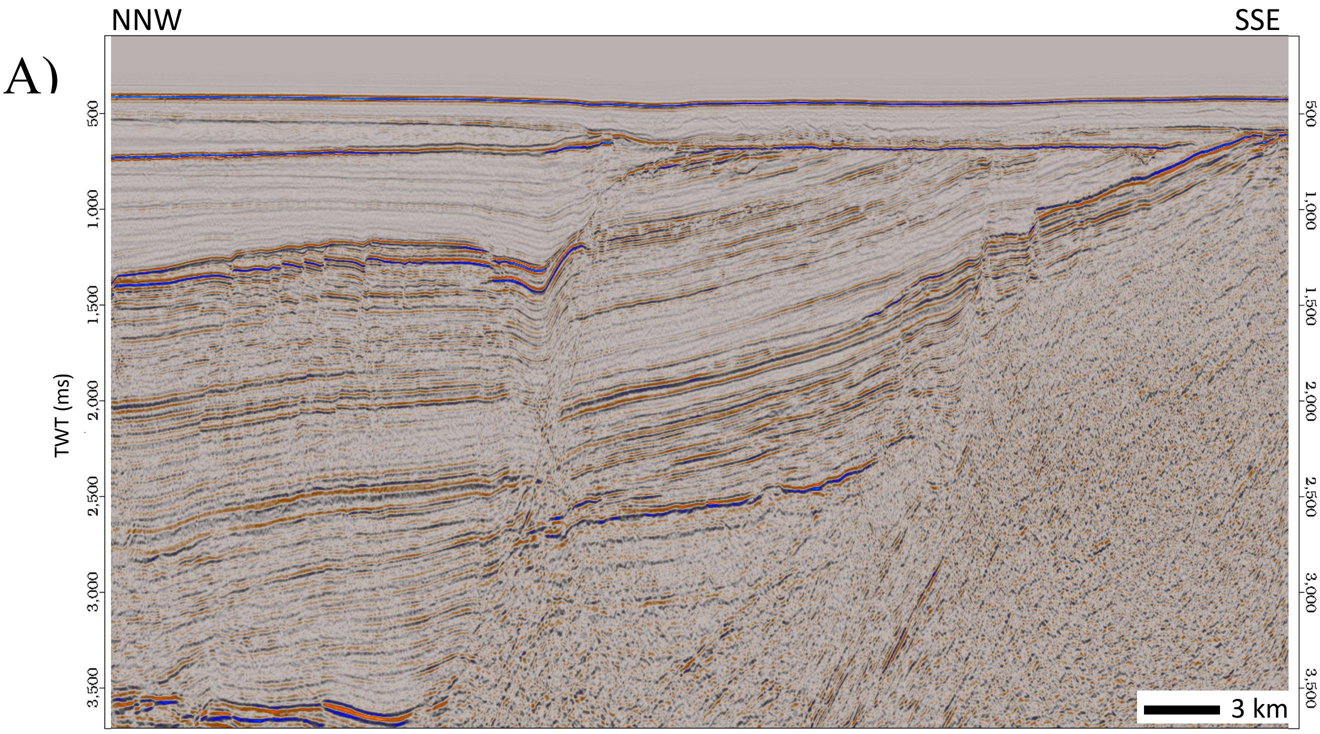


Figure 17: A) Uninterpreted and B) interpreted seismic line BSS01-137. No observed indications of syn-depositional activity associated with FF2. However, there is an observed decrease in overall thickness from the outer towards the inner platform. This decrease in overall thickness is thought to be related to the geometry of the platform, rather than being fault related. Vertical exaggeration 8x. See Figure 14 for location of line.



Top SU4
Base SU4
Direction of fault displacement

Figure 18: A) Uninterpreted and B) interpreted seismic line BSS01-113. The thickness of the interval appears constant across the faults of FF2. The decrease in overall thickness of the interval from outer to inner platform is thought to be related to the geometry of the platform, rather than being fault controlled. Vertical exaggeration 8x. See Figure 14 for location of line.



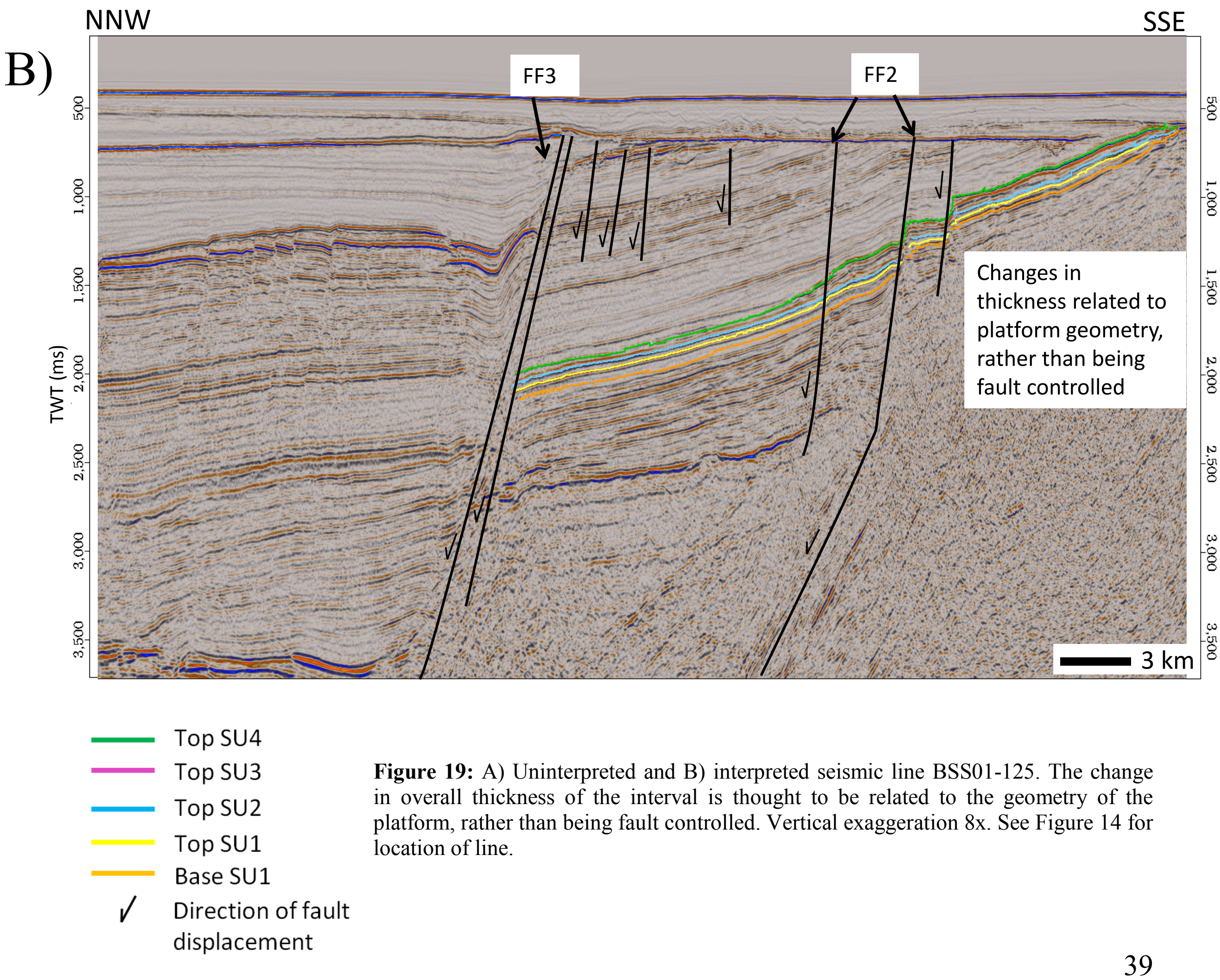
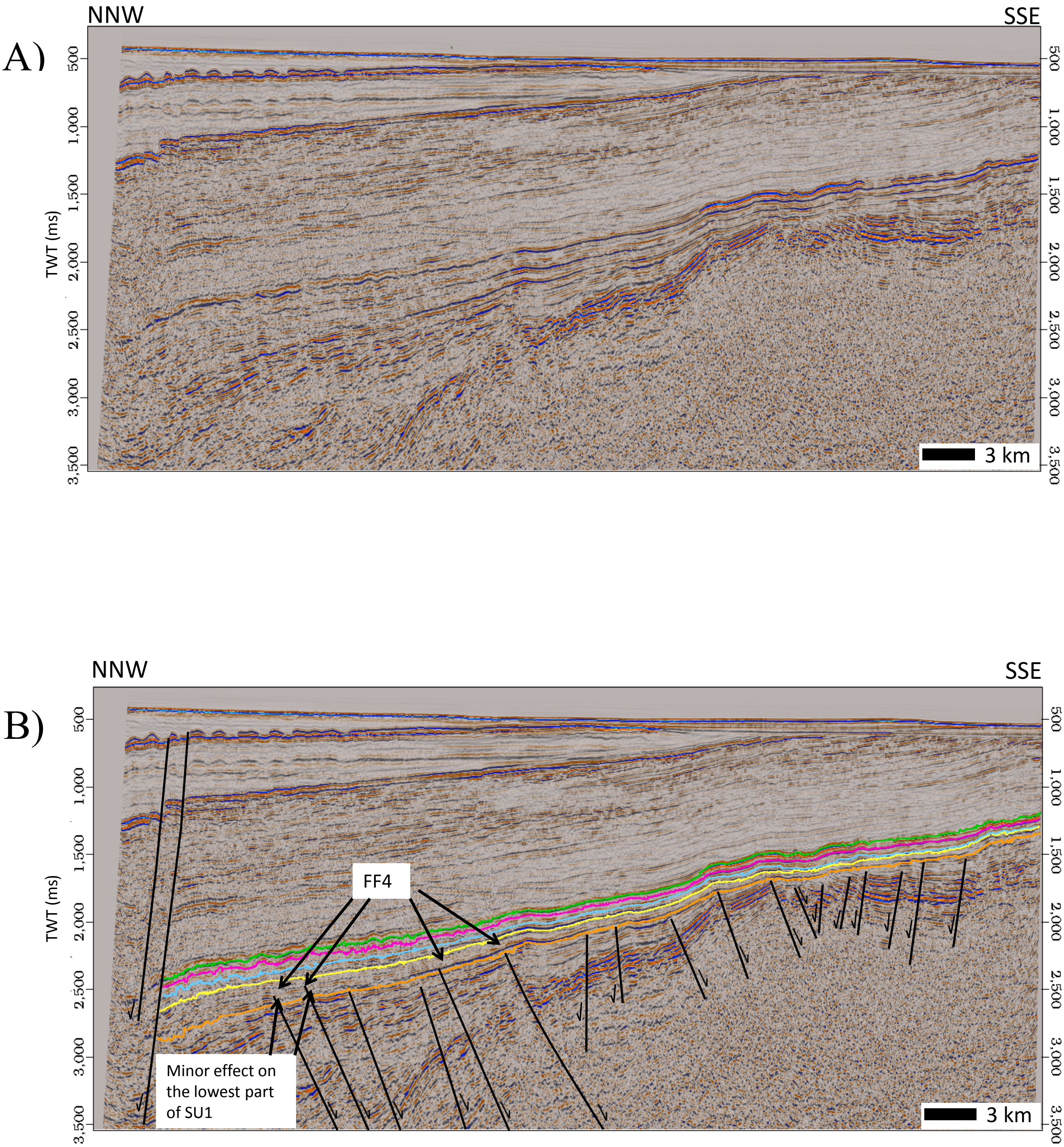


Figure 19: A) Uninterpreted and B) interpreted seismic line BSS01-125. The change in overall thickness of the interval is thought to be related to the geometry of the platform, rather than being fault controlled. Vertical exaggeration 8x. See Figure 14 for location of line.



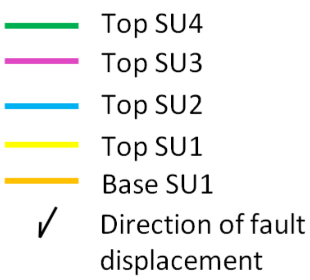


Figure 20: A) Uninterpreted and B) interpreted seismic line BSS01-145. The faults of FF4 seem to have been predominantly active pre-deposition of the Upper Paleozoic succession. However, minor influences on the lower part of SU1 are observed, indicating activity in the earliest stages of SU1 deposition. Vertical exaggeration 8x. See Figure 14 for location of line.

4.3 Stratigraphic framework

The stratigraphic observations will be discussed for each of the three defined provinces. However, throughout this study the main focus has been towards mapping the distribution of the Late Paleozoic carbonate intervals, and eventually the eastern province thus became the most studied province. The observations for the eastern province will be sub-divided into descriptions of well character, seismic character, and time structure and thickness maps for each of the defined units. For the central and western provinces, on the other hand, the observations will be presented in more general terms. There will be a main focus on the most remarkable observed stratigraphical features, as only one sequence appears to be present, and the limited well control in these provinces.

4.3.1 Eastern province

On the eastern Finnmark Platform, the Carboniferous-Permian biogenic interval has been sub-divided into four seismic units; SU1 to SU4 (Figures 7 and 8). These units are similar to the four major seismic units recognized by Samuelsberg et al. (2003). The four units are bounded by five horizons: Top Billefjorden (orange), Intra Gipsdalen (yellow), Near top Gipsdalen (blue), Top Bjarmeland (pink), and Near top Tempelfjorden (green) (Figure 8). A summary of the main characteristics of the observed seismic units on the eastern province is given in Table 5.

For each of the seismic units, time structure maps have been created across the entire eastern province. Time thickness maps, on the other hand, have been created from the 3D cube ST9802 (see Figure 2 for location). This 3D cube represents the transition from proximal to more distal parts of the platform, and is hence thought to be a good representation of thickness variations across the eastern province. The extent of the study area, distance between the 2D seismic lines, grid-size, and thin (often less than 100 ms TWT) units made creation of representative time thickness maps across the entire province challenging. The location of the various seismic lines referred to in section 4.3.1 is shown in Figure 21.

4.3.1.1 SU1

Well character

In shallow core 7029/03-U-02, the lower boundary of seismic unit one (SU1) corresponds to the boundary between the underlying Billefjorden Group characterized by a conglomeratic unit with coal fragments, and the overlying siltstone-dominated Ugle Formation, part of the Gipsdalen Group (Larssen et al., 2002). An abrupt change in log character defined by decreased density and interval transit time, and corresponding uniformly higher gamma log readings, is characteristic (Larssen et al., 2002). The boundary between the Ugle Formation and the stratigraphically overlying Falk Formation is also identified in core 7029/03-U-02 (Bugge et al., 1995; Larssen et al., 2002). This boundary represents an abrupt change in overall lithofacies and color, as there is a transition from non-marine red-colored silty shales towards marine grey-colored silty shales (Larssen et al., 2002). Wells 7128/4-1 and 7128/6-1, in addition to shallow core 7030/03-U-01, also encountered the grey-colored silty shales of the Falk Formation. Accordingly, in the eastern province, SU1 is represented by a noisy log pattern (Figures 7 and 8) as it represents interfingering of siliciclastics and carbonates (Larssen et al., 2002). A changing depositional setting from non-marine to marine, with increasingly higher content of carbonates, is represented by a change towards overall lower gamma-ray readings (Figures 7 and 8).

Seismic character

Based on tie to wells 7128/4-1 and 7128/6-1, SU1 correlates to the lower part of the Gipsdalen Group (Figure 8). The base of SU1 is interpreted as a relatively strong trough (Figure 8), which is characterized by a high amplitude seismic reflector with relatively high continuity (Figures 22, 23, 24 and 25). The basal reflector of SU1 (Top Billefjorden horizon) represents an unconformity where onlap, downlap, and toplap relationships have been observed (Figures 22, 23, 24 and 25). Internally, SU1 is characterized by a discontinuous low to medium amplitude reflection pattern in the lower part, while the reflections appear more continuous and have higher amplitudes towards the upper part of the unit (Table 5). Predominantly towards the northern part of the platform, small-scale isolated mounded features have been observed towards the upper part of the unit (Figures 22 and 24).

Time structure and thickness maps

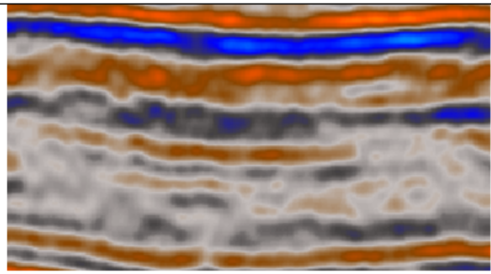
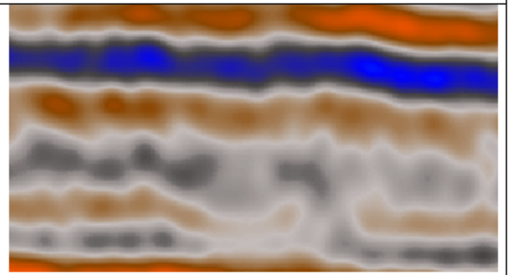
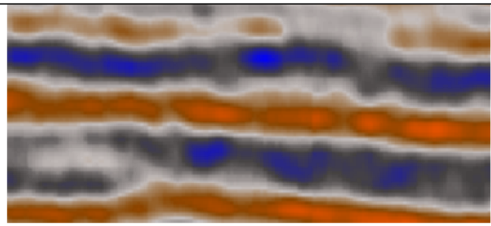
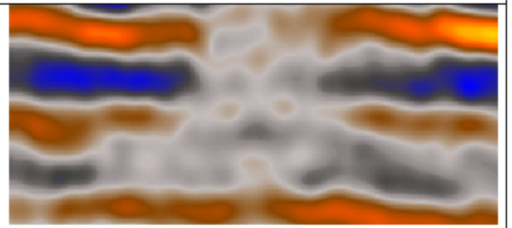
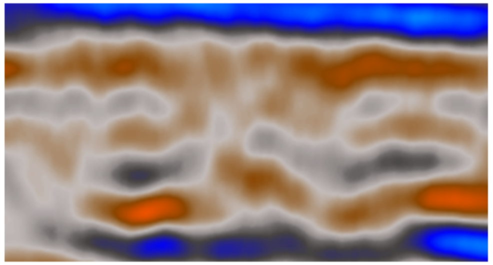
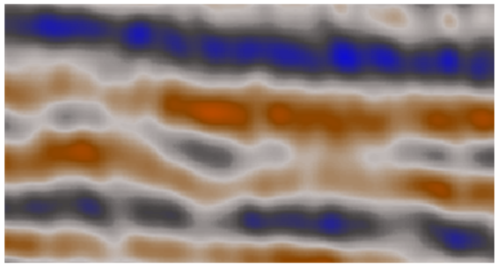
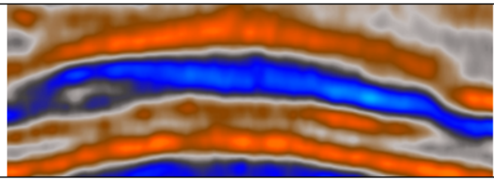
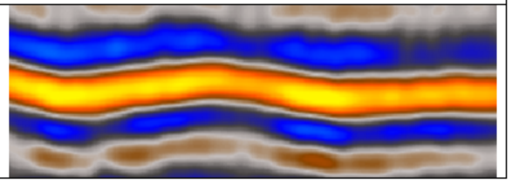
A time structure map of the SU1's upper boundary (Intra Gipsdalen horizon) is shown in Figure 26A. The map reveals a monocline platform, in which the unit is gently dipping northwards. In the eastern province, SU1 is affected by FF2 and FF3 (Figure 26A).

The thickness of the unit varies across the platform; SU1 appears thin, less than 50 ms TWT, on the inner platform (Figures 23 and 26B) and across structural highs (Figure 24), whereas a gradual increase in thickness has been observed towards the northern part of the platform (Figure 26B). In the northern part of the platform, the unit appears in excess of 150 ms TWT (Figure 22). In addition, indications of thickness variations across faults have been observed (Figure 23).

Interpretation

The basal reflector of SU1 represents decreased acoustic impedance between the underlying mainly grey fluvial siliciclastics within the Lower Carboniferous Billefjorden Group and the overlying mainly shallow-marine sandstones within the Bashkirian-Kasimovian part of the Gipsdalen Group (Figure 8). This contact is associated with a drastic change in paleoclimate from warm and humid towards warm and arid/semi-arid conditions (Larssen et al., 2002). The change in seismic signature between the lower and upper part of the unit is thought to represent a gradual change from dominance of siliciclastics in the lowermost part, towards increasing marine influence with carbonates and evaporites replacing the clastics in the uppermost part. The transitional lithological change from clastics towards carbonate and evaporite facies has been reported as being characteristic for the Falk Formation (Larssen et al., 2002). The proportion of siliciclastics seems to be larger updip on the platform, while favorable conditions for carbonate buildups dominated the basinal margins. Consequently, the different siliciclastic provenance areas were likely drowned at different times across the platform. The observed indications of thickness variations across faults, suggest activity during the earliest stages of deposition of SU1. Based on this, SU1 is thought to represent a late syn-tectonic unit.

Table 5: Overview of the main characteristics of the four seismic units that have been identified in the eastern province.

Seismic unit	Seismic reflection characteristics	Interpretation	Example from 2D data	Example from 3D data
SU1	Discontinuous low-medium amplitude reflection pattern in the lower part, medium-high amplitude semi-continuous reflectors towards the upper part	Mixture of shallow marine siliciclastics, carbonates, and minor evaporitic layers. More carbonate dominated in the upper part		
SU2	Medium-high amplitude semi-continuous sub-parallel reflectors combined with sections of lower amplitude reflections, and mounded features.	Warm-water carbonates, carbonate buildups, and evaporites		
SU3	Semi-transparent. Medium-low amplitude discontinuous reflectors bounded by medium-high amplitude semi-continuous reflectors. Isolated mounded features with chaotic internal signature.	Cool-water carbonates, and carbonate buildups		
SU4	Sub-parallel high to medium amplitude continuous reflectors. Isolated mounded features.	Spiculitic chert, and spiculitic limestone mounds		

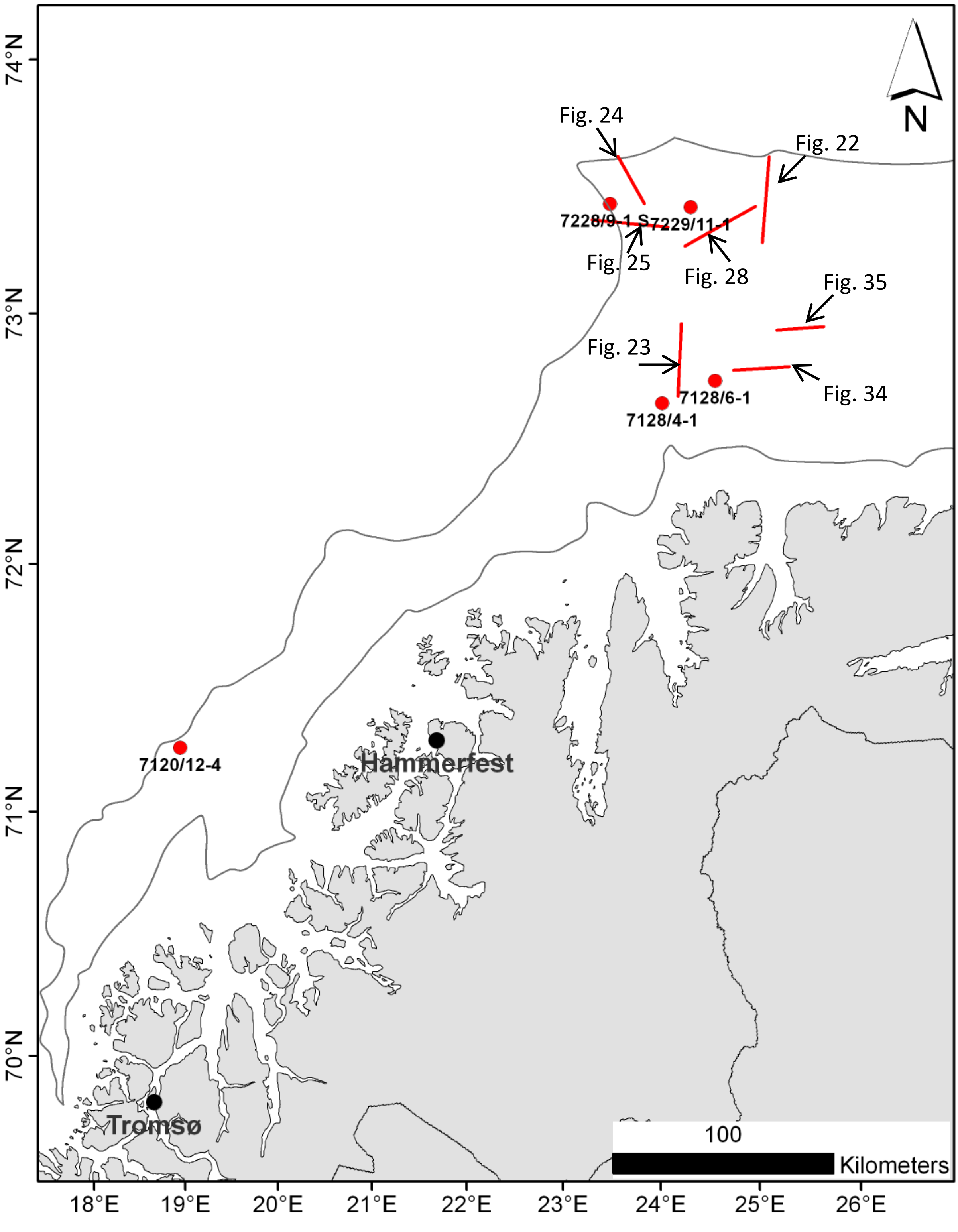
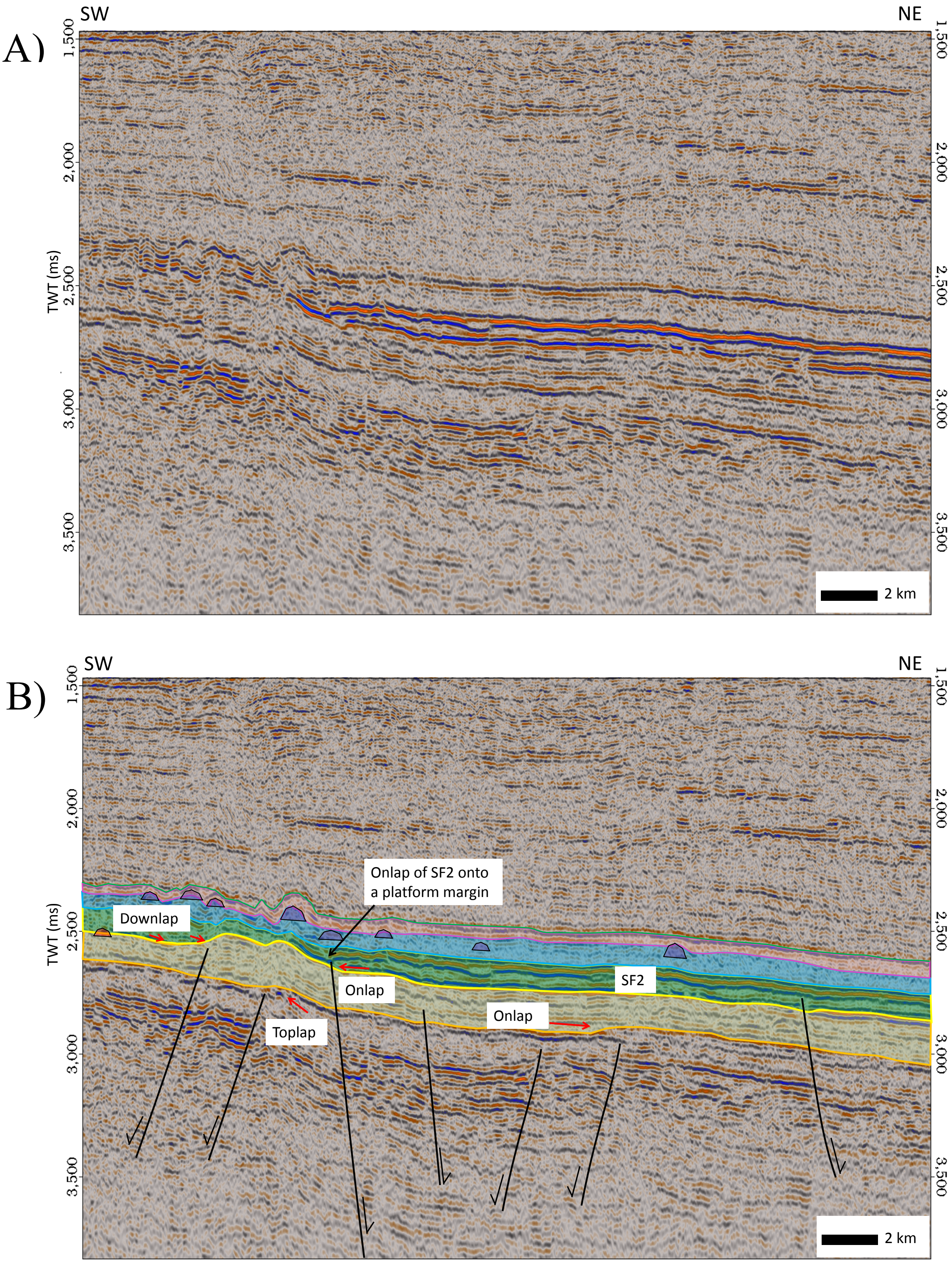


Figure 21: Locations of seismic lines referred to in section 4.3.1.



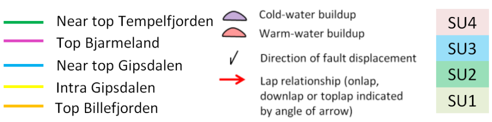
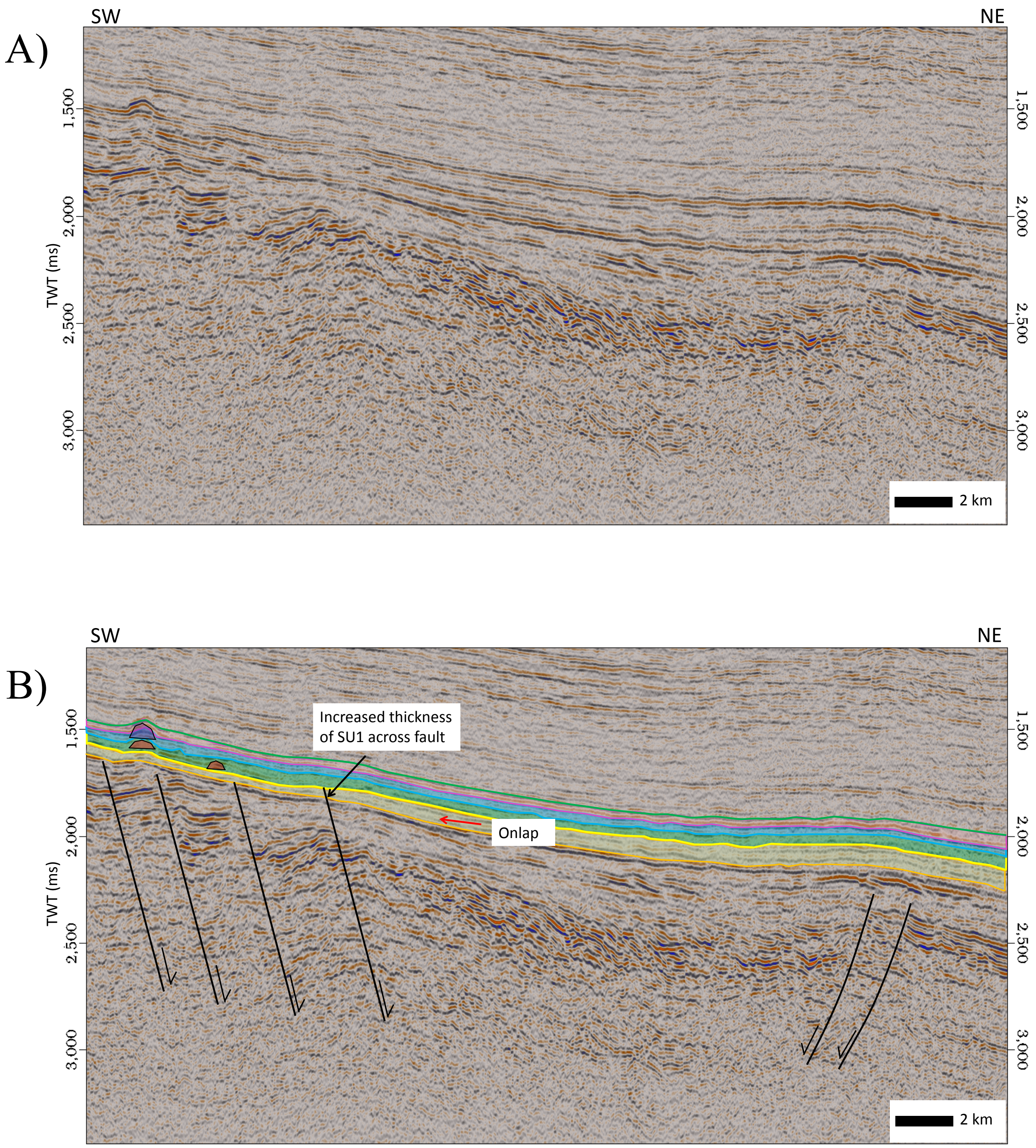


Figure 22: A) Uninterpreted and B) interpreted seismic line FEC90-102. The thickness of SU1 appears in excess of 150 ms TWT, contrasting significantly lower thickness on the inner platform areas. SU2 is represented by seismic facies two (SF2), which seems to onlap onto a platform margin. Buildups seem to favor growth on a structural high. See text for more details. Vertical exaggeration 8x. See Figure 21 for location of the line.



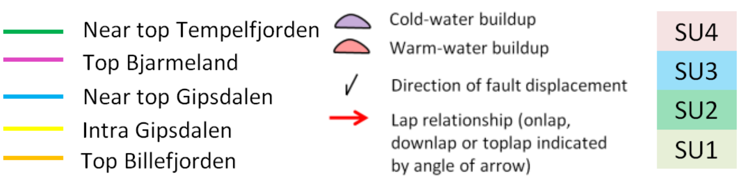


Figure 23: A) Uninterpreted and B) interpreted seismic line FEC89-110. SU1 appears thin over the structural high. There is an observed increase in thickness across some of the faults, suggesting activity during earliest stages of deposition of SU1. Carbonate buildups seem to favor growth on top of each other, and on structurally elevated locations. See text for more details. Vertical exaggeration 8x. See Figure 21 for location of the line.

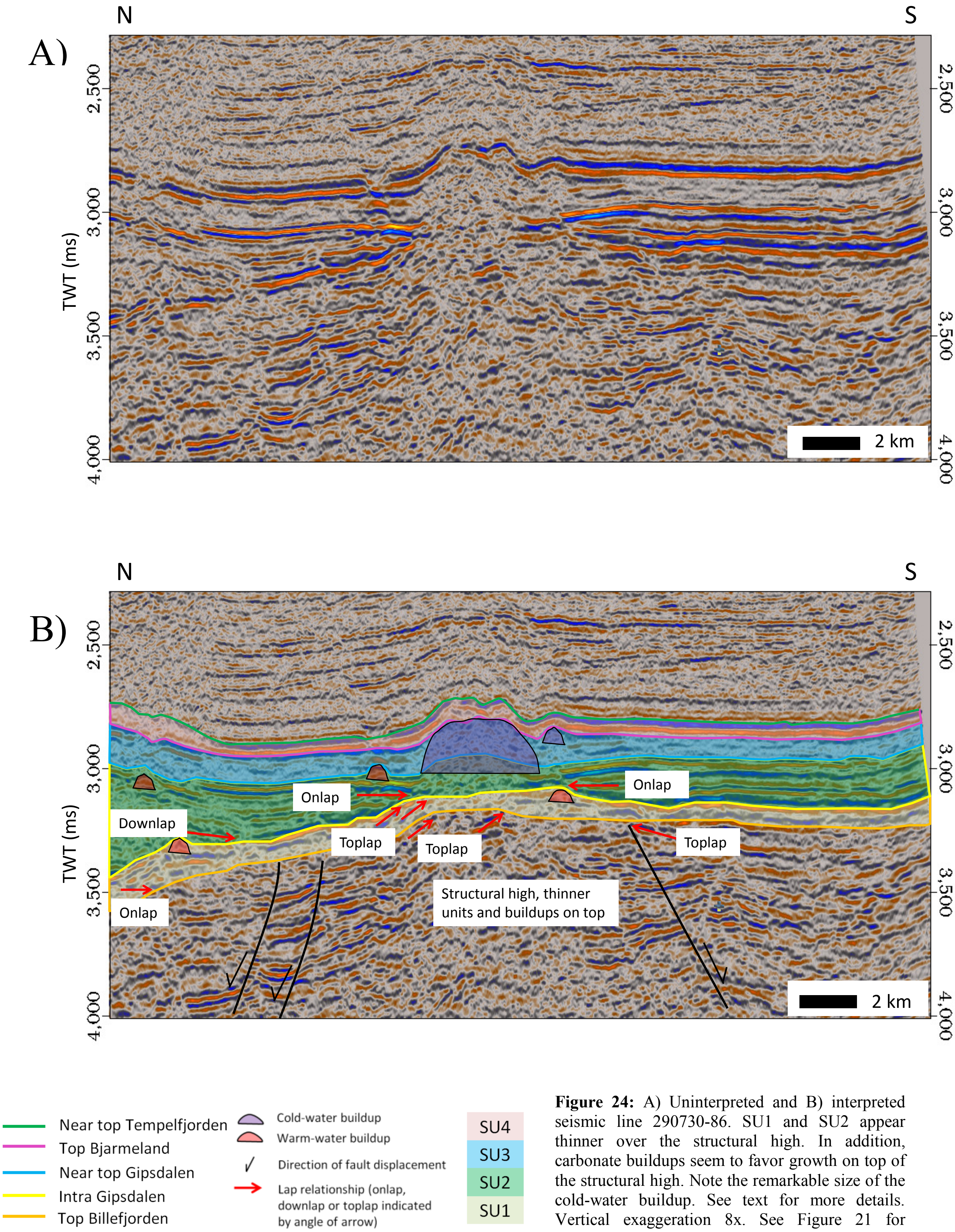


Figure 24: A) Uninterpreted and B) interpreted seismic line 290730-86. SU1 and SU2 appear thinner over the structural high. In addition, carbonate buildups seem to favor growth on top of the structural high. Note the remarkable size of the cold-water buildup. See text for more details. Vertical exaggeration 8x. See Figure 21 for location of the line.

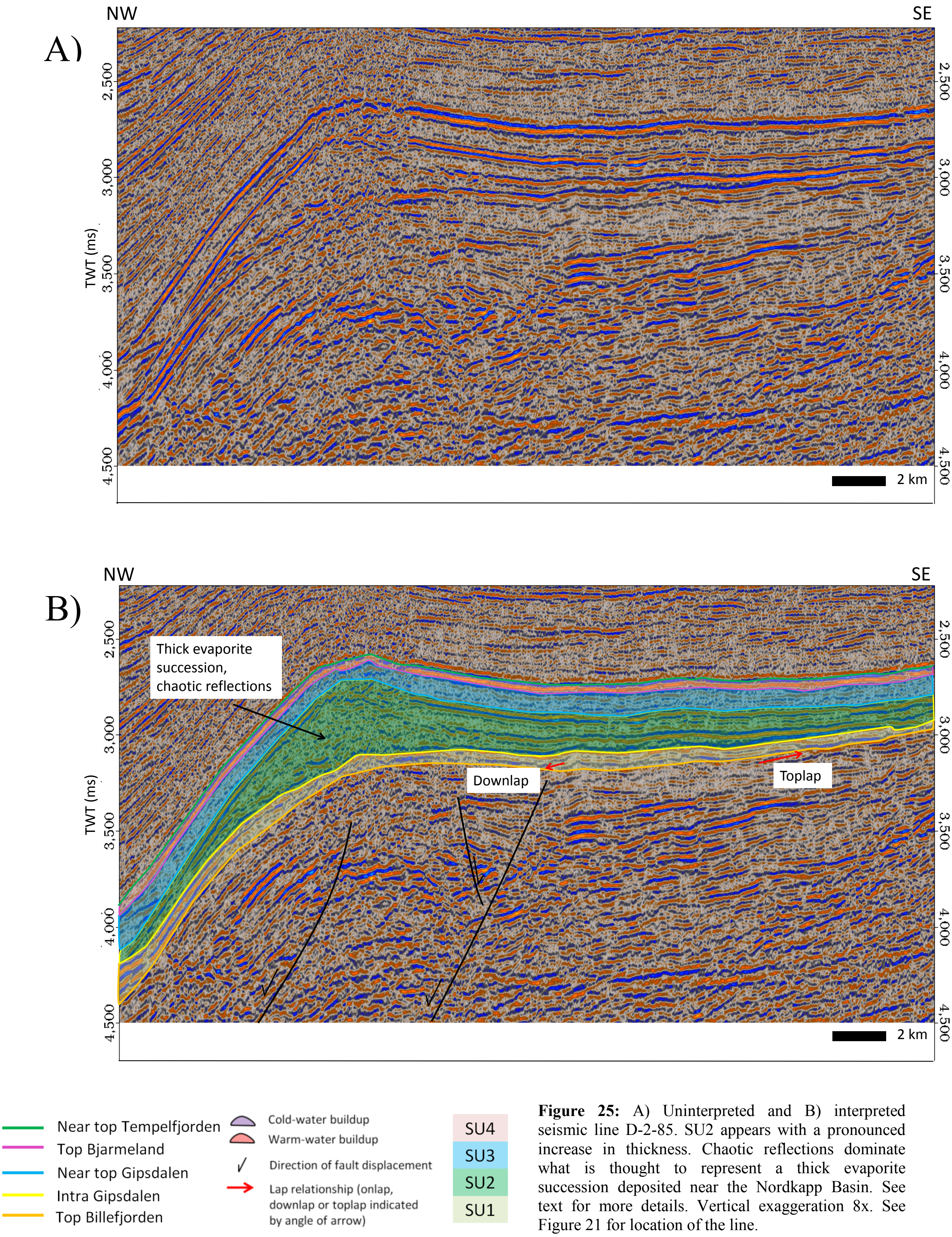
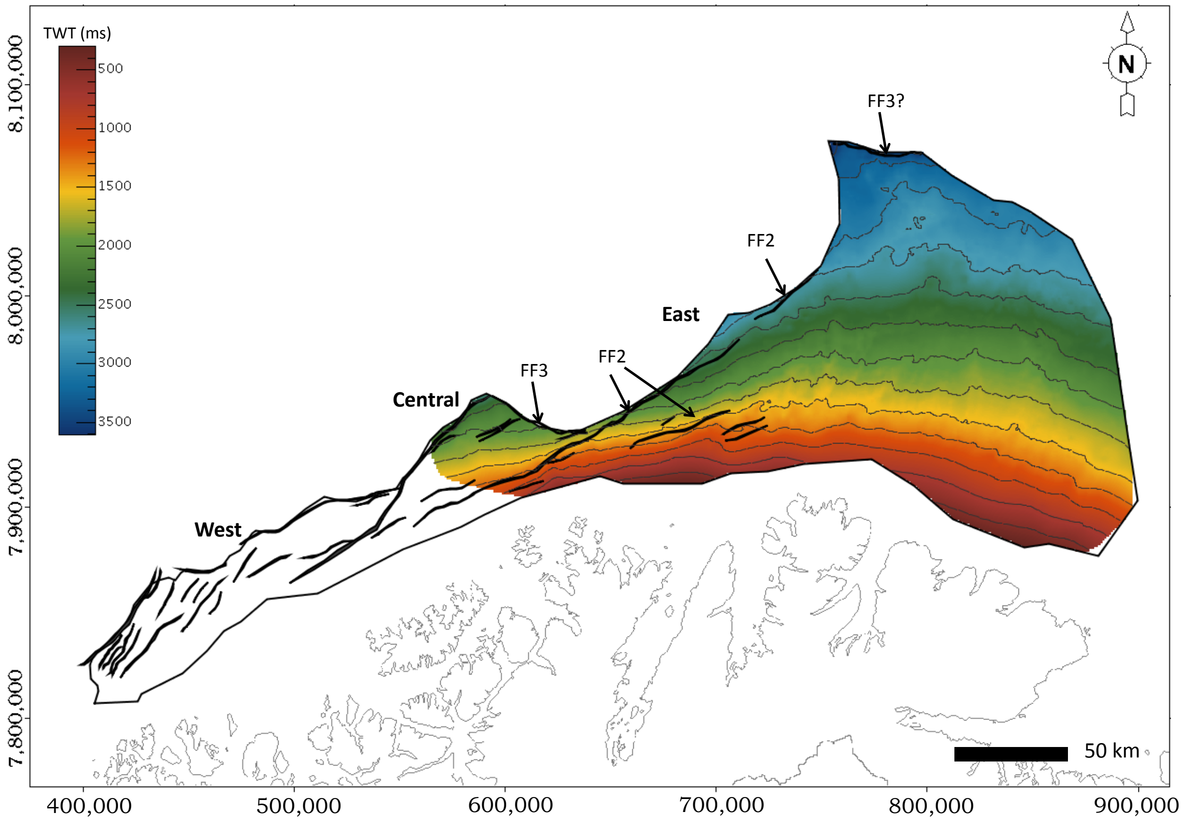


Figure 25: A) Uninterpreted and B) interpreted seismic line D-2-85. SU2 appears with a pronounced increase in thickness. Chaotic reflections dominate what is thought to represent a thick evaporite succession deposited near the Nordkapp Basin. See text for more details. Vertical exaggeration 8x. See Figure 21 for location of the line.

A)



B)

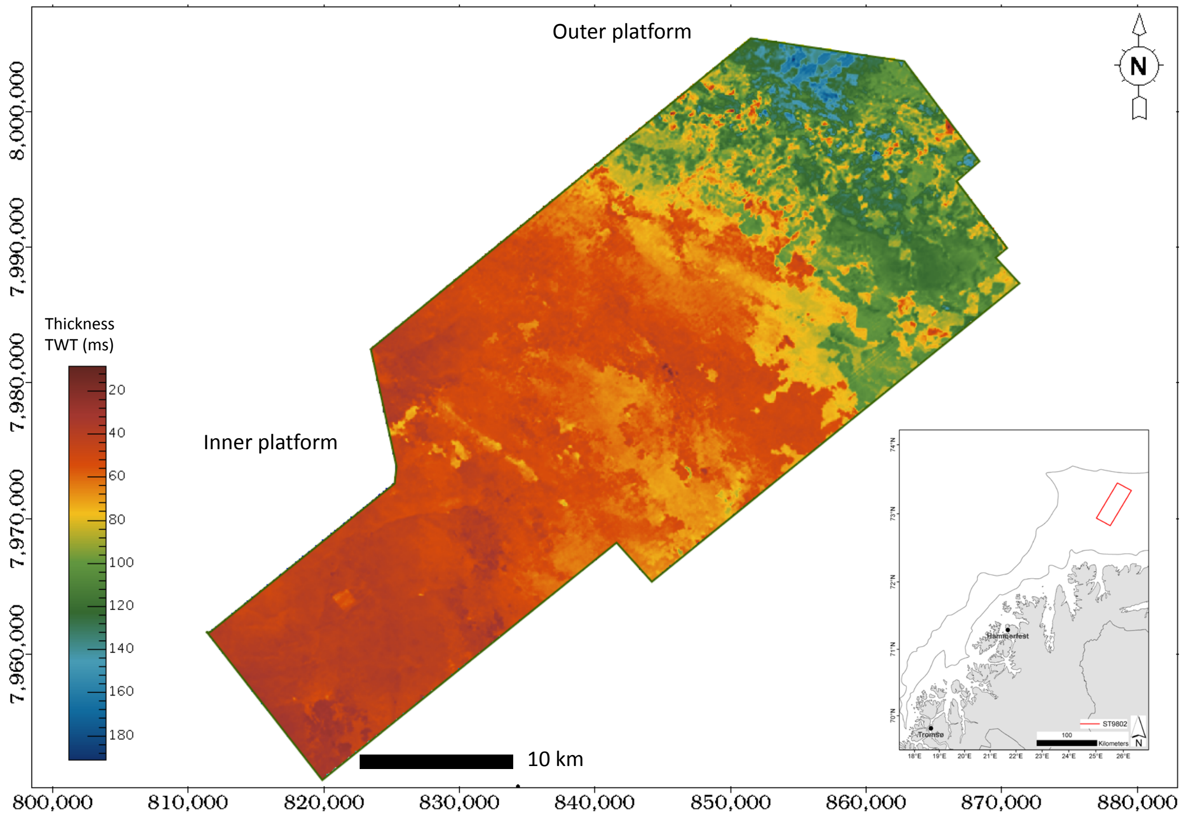


Figure 26: A) Time structure map of top SU1 (Intra Gipsdalen horizon). A monocline platform geometry is revealed. In the eastern province, SU1 is affected by FF2 and FF3. B) Time thickness map of SU1 from 3D cube ST9802. The location of the 3D cube can be seen from the inset map in the lower right. SU1 is thin, often less than 50 ms TWT on the inner platform, whereas an overall gradual distal increase in thickness is observed. In the outer platform areas, the thickness is generally around 100 ms TWT. The patchy thickness variation in the outer platform areas is a result of an overlying evaporite succession, which makes a consistent interpretation challenging. Coordinate system UTM 34 ED 50.

4.3.1.2 SU2

Well character

The boundary between the underlying SU1 and the overlying seismic unit 2 (SU2) was encountered by wells 7128/4-1 and 7128/6-1, in addition to the shallow cores 7030/03-U-01, 7029/03-U-02, and 7129/10-U-02 (Larssen et al., 2002). This boundary is defined by an abrupt change towards overall lower gamma-ray readings (Figure 8) accompanied by significantly higher interval transit times (Larssen et al., 2002). Overall, the SU2 interval is characterized by a less noisy log pattern compared to the underlying SU1 unit (Figure 8). The observed log characteristics are indicative of a dominance of carbonates.

Seismic character

According to tie to wells 7128/4-1 and 7128/6-1, SU2 correlates to the Gzhelian - Asselian part of the Gipsdalen Group (Figure 8). The basal reflector of SU2 is interpreted as a trough (Figure 8), and it is characterized by a medium amplitude reflector with medium continuity. Internally, reflections are observed to downlap and onlap the lower boundary (Figures 22 and 24). Two main seismic facies have been identified within SU2; seismic facies 1 (SF1) is characterized by semi-continuous sub-parallel amplitude seismic reflections (Table 6), while seismic facies 2 (SF2) is characterized by a set of continuous high amplitude reflections that occur with either a sub-parallel relationship or as slightly divergent reflectors creating lense-shapes (Table 6). SF1 represents the most characteristic reflection pattern of SU2, and has been observed across most of the eastern province (Figure 27). SF2, on the other hand, has only been observed in a localized area towards the most distal part of the platform (Figure 27). Towards the south, the laterally restricted SF2 seems to onlap a platform margin (Figure 22).

Local small-scale buildups characterized by a low amplitude chaotic reflection pattern (Table 6) have been observed both within SF1 and in relation with SF2 (Figures 23, 24 and 28). Their occurrence is best observed towards the northern part of the platform. Figure 29 shows localities of observed SU1 and SU2 buildups in the eastern province. These buildups seem to be randomly scattered across the eastern platform.

Time structure and thickness maps

SU2 has been observed across the entire eastern platform, and a time structure map of the top of the unit (Near top Gipsdalen horizon) is shown in Figure 30A. A similar monoclinal appearance of the platform as observed in the time structure map of SU1 is shown. In the eastern province, SU2 is affected by FF2 and FF3 (Figure 30A).

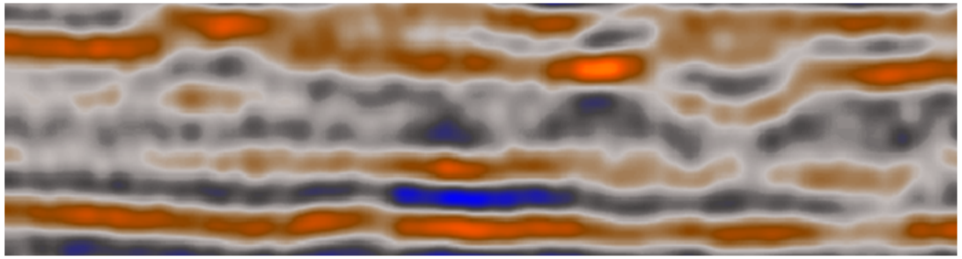
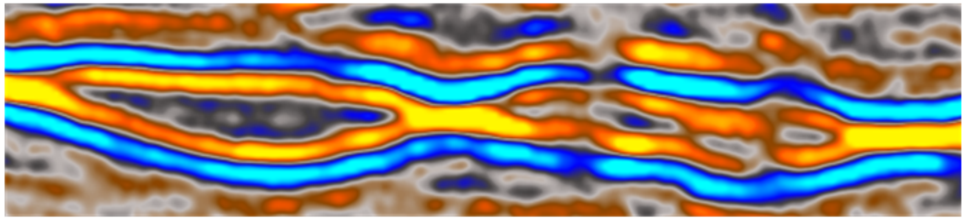
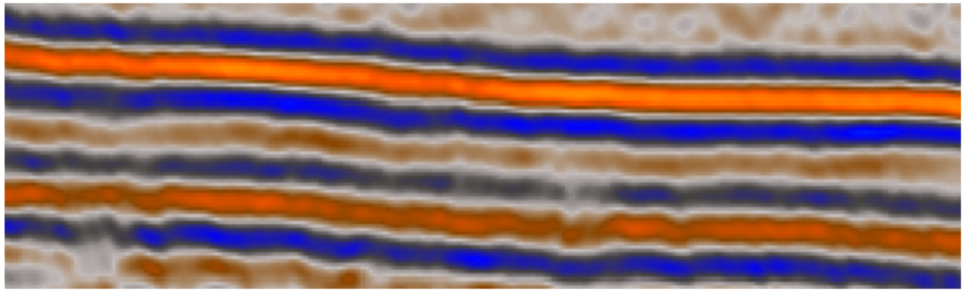
The time thickness map (Figure 30B) shows the same gradual increase in thickness towards the north, as observed for SU1. However, for SU2 there has not been observed any indications of thickness variations across faults. Towards the northernmost part of the platform, in close proximity to the adjacent Nordkapp Basin, SU2 reveals pronounced increase in thickness (Figure 25). Here local thickness of more than 400 ms TWT has been observed (Figure 25). In these areas the unit is characterized by a more chaotic reflection pattern (Figure 25) than what has been observed elsewhere on the platform.

Interpretation

The high amplitude continuous reflections characteristic of SF2 is thought to represent evaporites deposited during times of lowstand. Initially, the evaporites were likely deposited in a sub-parallel relationship. The lense-shapes are thought to represent a post-depositional effect, probably being caused by differential loading on top of parts of the evaporites. Scattered carbonate buildups might be responsible for such a differential loading effect. The pronounced increase in thickness of SU2 near the Nordkapp Basin is probably also representing deposition of a thick evaporite succession.

Within SU2, wells 7128/4-1 and 7128/6-1, in addition to several of the IKU shallow cores, penetrated sub–seismic scale buildups dominated by algae and *Palaeoaplysina* (Bugge et al., 1995; Ehrenberg et al., 1998). This gives indications of possible widespread distribution of sub-seismic buildups across the eastern Finnmark Platform. The buildups dominated by algae and *Palaeoaplysina* likely formed in tropical, warm water environments (Samuelsberg et al., 2003), and the observed buildups within the upper part of SU1 and SU2 are hence thought to represent warm-water carbonate buildups. Based on this, the observed occurrence of warm-water buildups shown in Figure 29 is likely highly underestimated. The different siliciclastic provenance areas were probably drowned at different times, giving rise to presence of the thickest carbonate-dominated successions on the distal parts of the platform. The absence of thickness variations across faults is indicative of SU2 representing a post-tectonic unit.

Table 6: Seismic characterization of the two observed facies within SU2; SF1 and SF2.

Seismic facies	Seismic reflection characteristics	Interpretation	Examples
SF1	Semi-continuous sub-parallel medium amplitude seismic events with local small-scale mounded features characterized by low amplitude and chaotic appearance.	Subtidal warm-water carbonates, and carbonate buildups, deposited during times when the platform was flooded.	
SF2	Continuous high amplitude reflectors, both present as sub-parallel reflectors and as slightly divergent forming convergent lense shapes.	Evaporites deposited during glacio-eustatic sea-level falls. The lense shapes are possibly caused by differential loading on top of the evaporites.	 

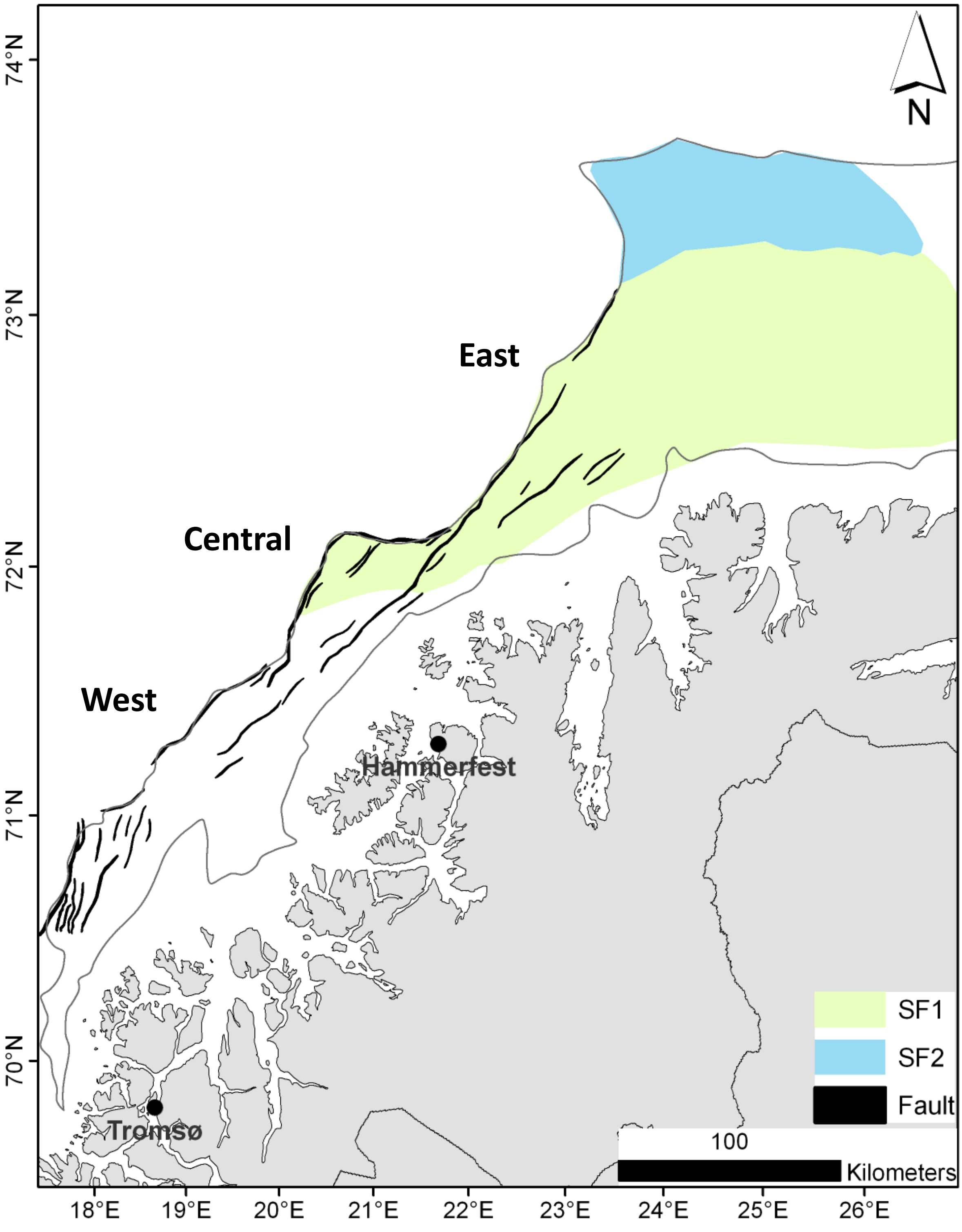
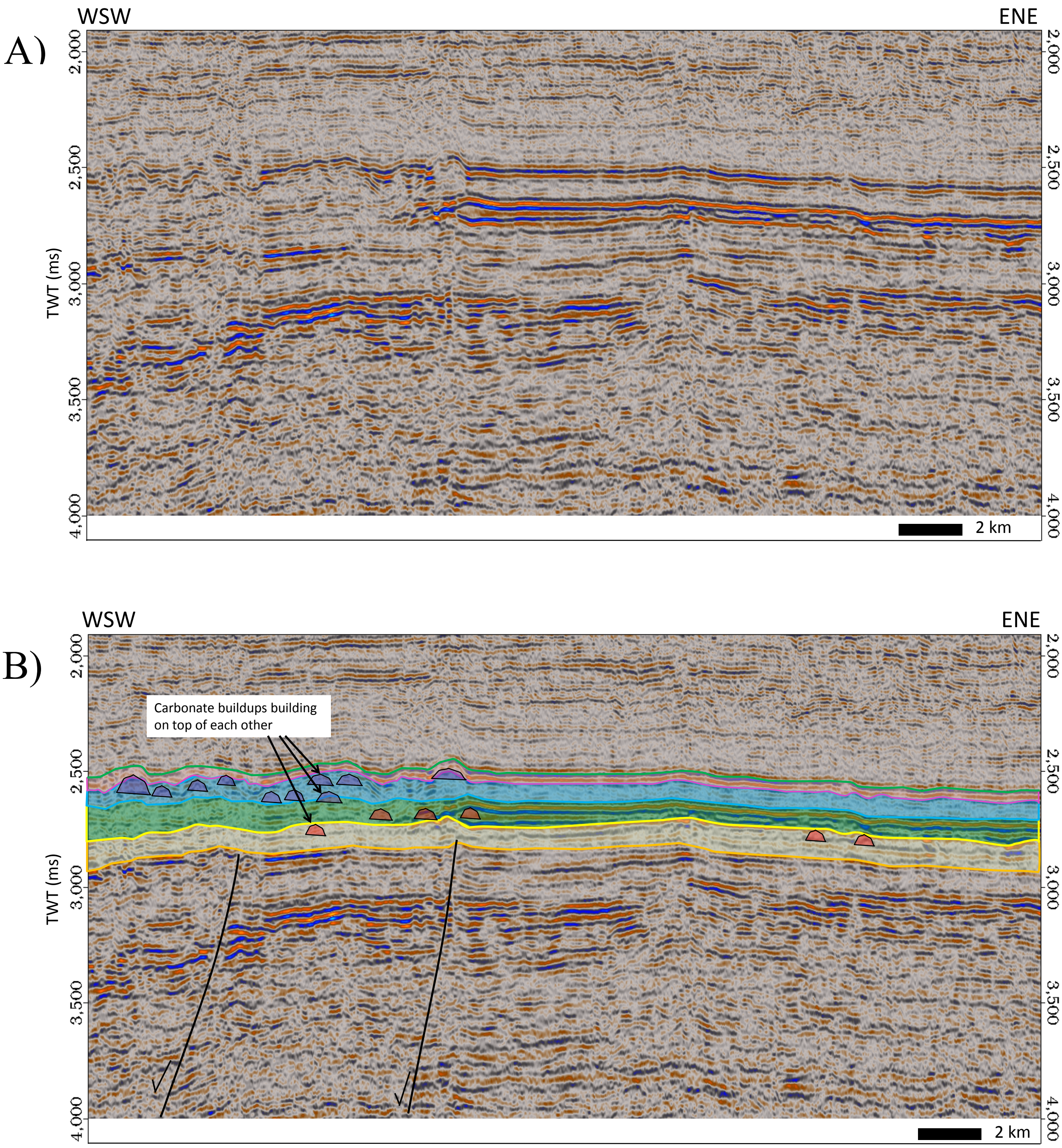


Figure 27: Observed distribution of the two facies within SU2; SF1 and SF2. SF1 is more widely distributed compared to SF2, which is only observed in a localized area on the outer platform.



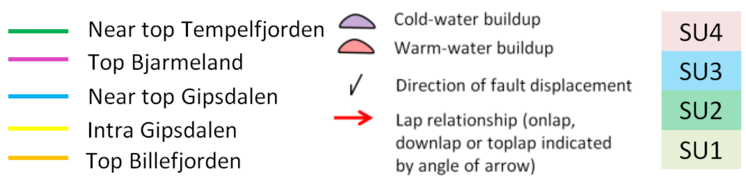


Figure 28: A) Uninterpreted and B) interpreted seismic line 7205-85_1. Carbonate buildups seem to favor growth on top of each other, and on structurally elevated highs. See text for more details. Vertical exaggeration 8x. See Figure 21 for location of the line.

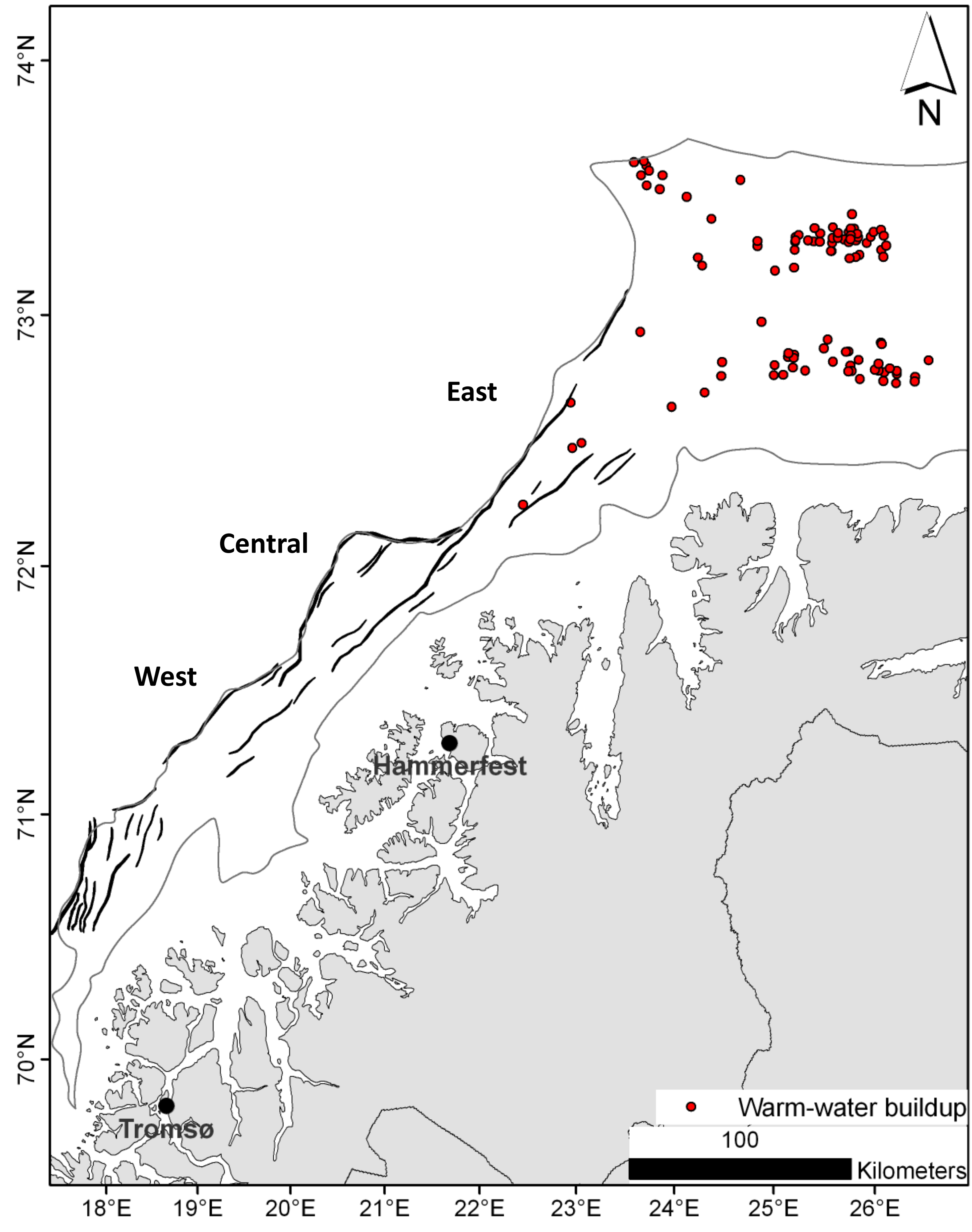


Figure 29: Observed warm-water (SU1 and SU2) buildups across the Finnmark Platform. These buildups appear randomly scattered across the eastern province.

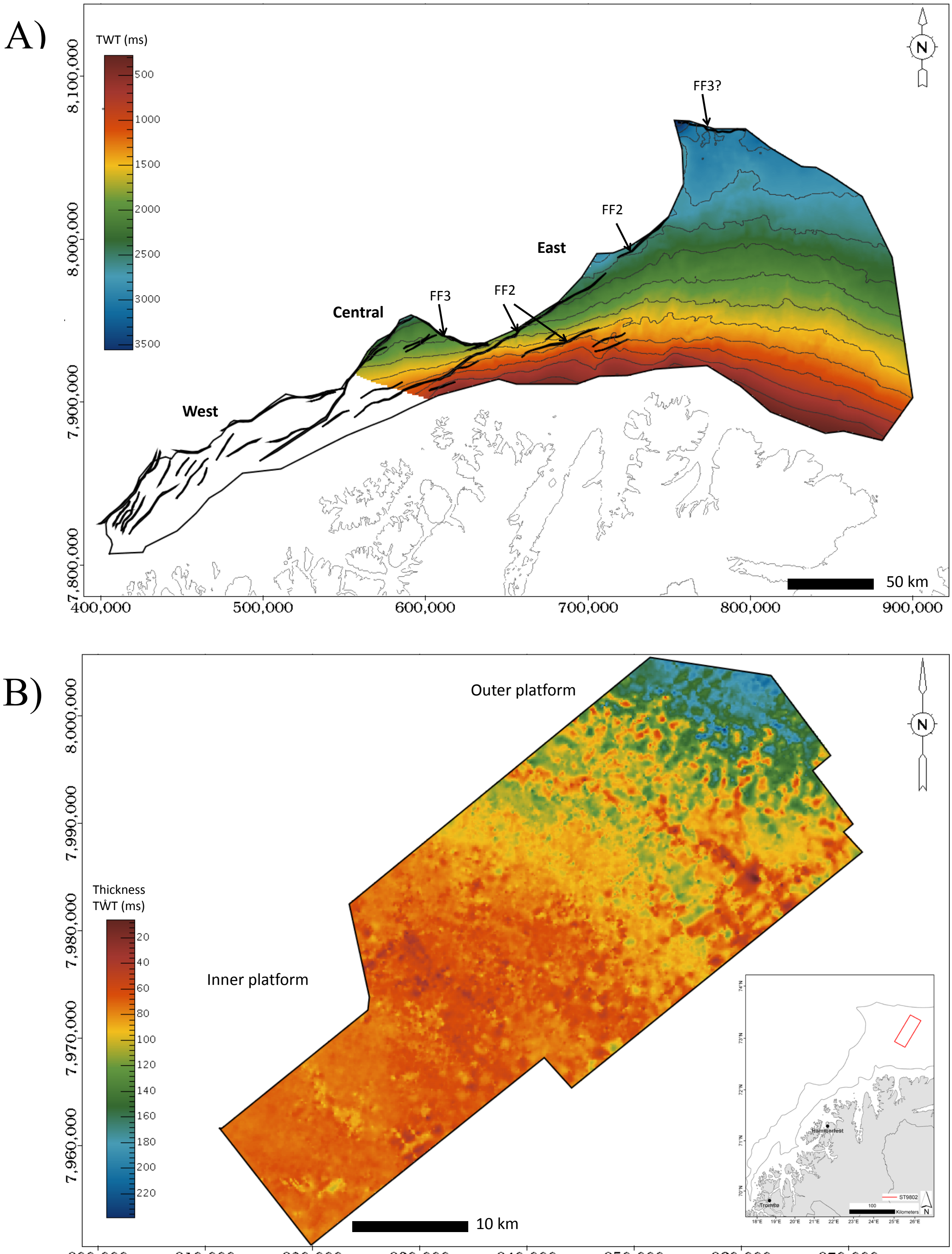


Figure 30: A) Time structure map of top SU2 (Near top Gipsdalen horizon). A monocline platform geometry is revealed. In the eastern province, SU2 is affected by FF2 and FF3. B) Time thickness map of SU2 from 3D cube ST9802. The location of the 3D cube can be seen from the inset map in the lower right. A gradual distal increase in thickness is observed. The patchy thickness variation in the outer platform area is a result of the evaporites within SU2, which makes a consistent interpretation challenging. Coordinate system UTM 34 ED 50.

4.3.1.3 SU3

Well character

The base of seismic unit 3 (SU3) is marked by a sharp and abrupt change towards uniformly lower gamma-ray readings compared to the underlying unit (Figure 8). Other characteristic log responses are decreased interval transit time in combination with lowered neutron porosity log readings (Larssen et al., 2002). Overall, the log pattern of SU3 appears uniform with little noise (Figure 8).

Seismic character

Based on tie to the exploration wells on the eastern platform, SU3 correlates to the uppermost part of the Gipsdalen Group in addition to the Bjarmeland Group (Figure 8). The lower boundary is interpreted as being defined by a peak (Figure 8). In the southern part of the platform, a medium amplitude reflector with medium continuity represents the basal reflector (Figure 23), whilst it on the northern part of the platform appears with higher amplitude and higher continuity as it in this part of the platform is interpreted to represent the top of the SU2 evaporite unit (SF2) (Figures 22 and 28). Internally, SU3 is characterized by a semi-transparent seismic reflection pattern (Table 5, Figures 22, 23, 24, 25 and 28). Discontinuous low to medium amplitude reflections occur in combination with mounded features with characteristic chaotic reflection signature (Table 5).

Figure 31 shows the observed SU3 buildups across the eastern province of the Finnmark Platform. It reveals that the buildups have been observed predominantly in the northern part of the platform, in addition to in the northwest, in close proximity to the adjacent Nordkapp Basin. The buildups have been observed to favor growth on top of structural highs and also on top of other buildups (Figures 22, 23, 24 and 28). Furthermore, the buildups have been observed in varying sizes; the largest ones being observed on the northern part of the platform. Figure 24 shows one of the largest observed SU3 buildups; it is approximately 3 km wide and has a height of near 250 ms TWT. Figure 32 shows how the buildups within SU3 form polygonal features; which is not evident from 2D seismic data. Several authors, including Samuelsberg et al. (2003), Colpaert et al. (2007) and Rafaelsen et al. (2008), have reported this polygonal geometry of the buildups within SU3. In addition, Elvebakk et al. (2002) reported similar geometrical features from the Loppa High.

Time structure and thickness maps

A time structure map of the upper boundary of SU3 (Top Bjarmeland horizon) is presented in Figure 33A. A similar overall structural trend of the platform as shown by the previous time structure maps is revealed. In the eastern province, SU3 is affected by FF2 (Figure 33A).

A time thickness map of the unit is shown in Figure 33B. Predominantly, the unit has a thickness in the range of 50-80 ms TWT; however the unit appears with a thickness of more than 150 ms TWT towards the northernmost part of the platform (Figure 33B). The greatest thicknesses occur in the distal platform areas where the buildups are localized (Figures 24 and 31).

Interpretation

SU3 represents a transition from underlying silty warm-water carbonates towards overlying cleaner cool-water carbonates (Larssen et al., 2002). On the northern part of the Finnmark Platform, the buildups within SU3 have been penetrated by well 7229/11-1 (Blendinger et al., 1997). Here they were found to be composed mainly of bryozoan-*Tubiphytes* grainstones and cementstones, in combination with packstones and grainstones rich in bryozoans (Blendinger et al., 1997). On the more proximal parts of the platform, wells 7128/4-1 and 7128/6-1, in addition to several IKU shallow cores, encountered packstones and grainstones with high content of bryozoans and crinoids (Bugge et al., 1995; Ehrenberg et al., 1998). The biota found within SU3 indicates that this unit was deposited under significantly colder climatic conditions than the underlying SU2 (Stemmerik, 1997). Consequently, the SU3 buildups are interpreted as cold-water carbonate buildups.

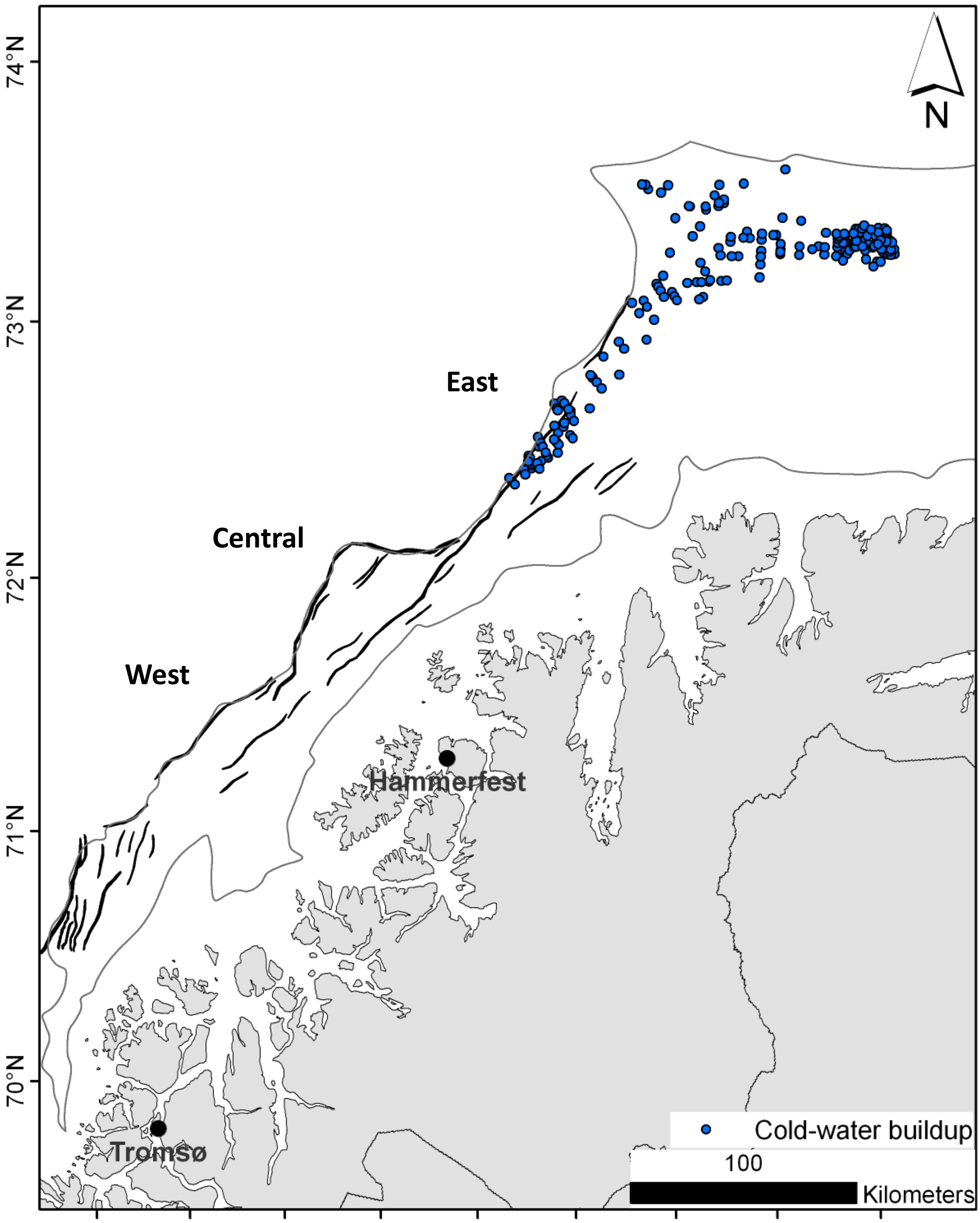


Figure 31: Observed cold-water (SU3) buildups across the Finnmark Platform. Note the predominant occurrence on the most distal parts of the platform.

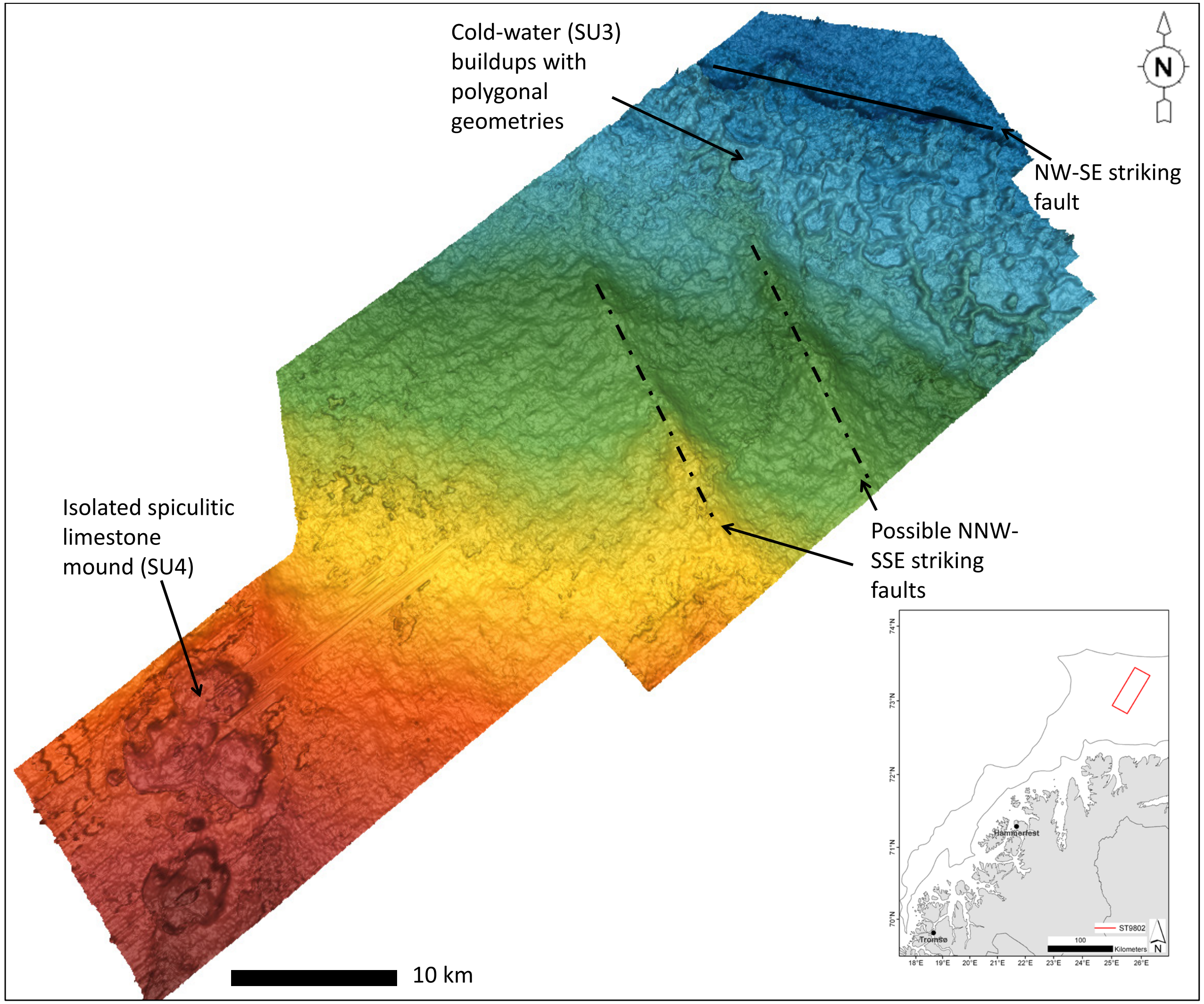


Figure 32: Time structure map of the Near top Tempelfjorden horizon in the 3D cube ST9802. Note how the cold-water carbonates within SU3 form polygonal features. The spiculitic limestone mound of SU4, on the other hand, appears more isolated. A NW-SE striking fault is present on the outer platform. In addition, two NNW-SSE oriented lineaments, possibly representing faults, are observed on the central platform. Vertical exaggeration 20x. The location of the 3D cube can be seen from the inset map in the lower right.

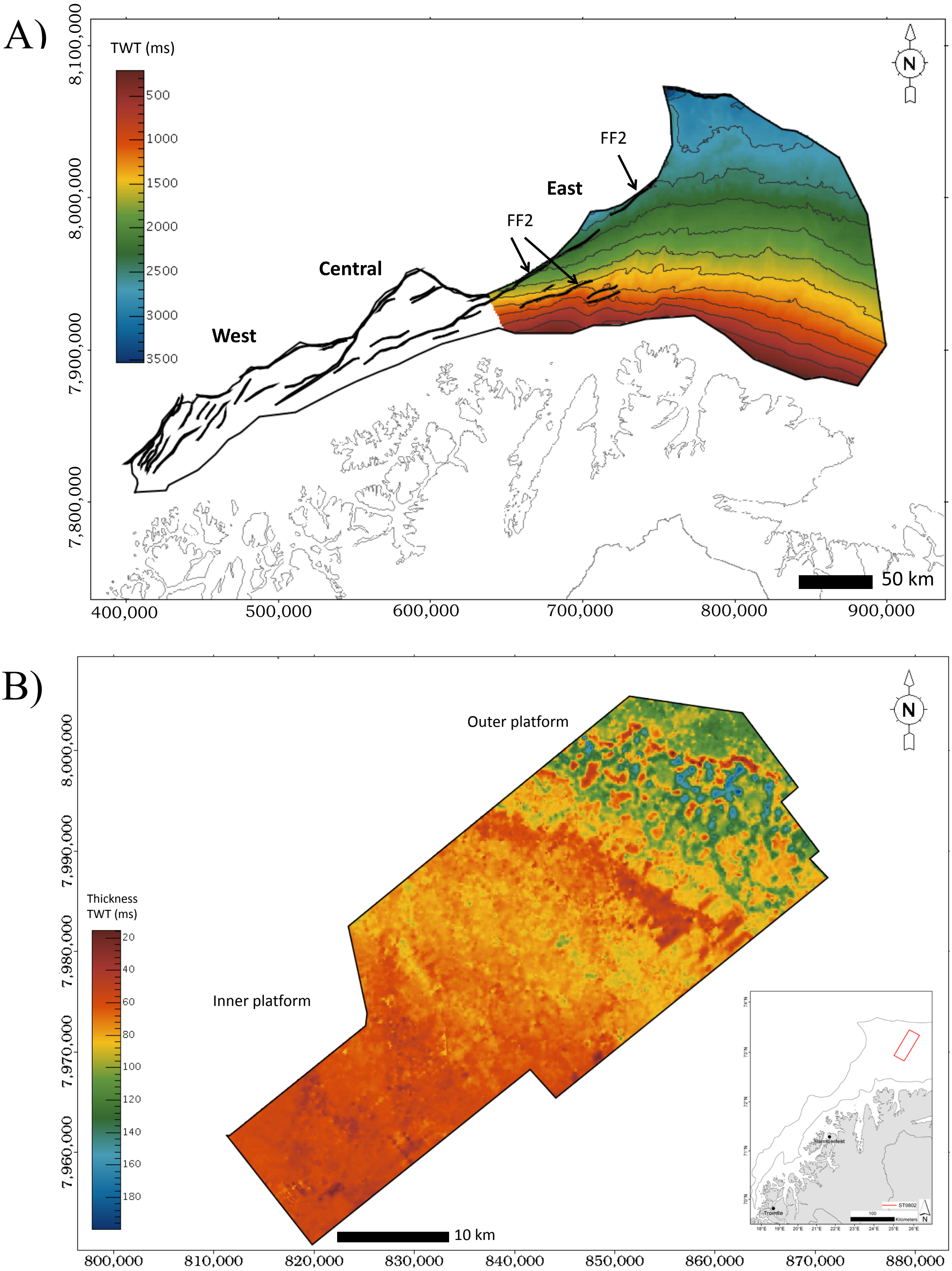


Figure 33: A) Time structure map of top SU3 (Top Bjarmeland horizon). A similar monocline platform geometry as shown by the other time structure maps is revealed. In the eastern province, SU3 is affected by FF2. B) Time thickness map of SU3 from 3D cube ST9802. Predominantly, SU3 has a thickness in the range of 50-80 ms TWT. Greater thicknesses occur in the most distal platform areas, where the buildups are localized. The patchy thickness variation in the outer platform area is a result of the evaporites within the underlying SU2, which makes a consistent interpretation challenging. The location of the 3D cube can be seen from the inset map in the lower right. Coordinate system UTM 34 ED 50.

4.3.1.4 SU4

Well character

The base of seismic unit 4 (SU4) is defined by an abrupt increase in the gamma-ray log response (Figure 8), accompanied by decreased interval transit time and density (Larssen et al., 2002). Both SU4 and SU3 reveal a characteristic "blocky" gamma-ray signature, however SU4 shows overall lower gamma-ray readings compared to the underlying SU3 unit (Figures 7 and 8). The upper boundary of SU4 is defined by a significant and sharp increase in gamma-ray readings (Figure 8), accompanied by increased density readings (Larssen et al., 2002).

Seismic character

According to tie to the exploration wells on the eastern Finnmark Platform, SU4 correlates to the Tempelfjorden Group (Figure 8). The basal reflector is interpreted as a peak (Figure 8) represented by a reflector with medium to high amplitude and high to medium continuity (Figures 24 and 25). Internally, SU4 is characterized by sub-parallel medium to high amplitude continuous reflectors (Table 5). The top of SU4 is interpreted as a peak (Figure 8), which is represented by a high amplitude reflector with high to medium continuity (Figures 22, 23, 24, 25 and 28).

Isolated mounded features with characteristic internal chaotic reflection pattern, and onlapping overlying reflectors, are another characteristic feature of SU4 (Figures 34 and 35). These mounds have been widely observed on the inner part of the platform, where they occur in an approximately 40 km wide east-west to northeast-southwest oriented belt (Figure 36). The observed mounds reveal pronounced differences in size (Figures 34 and 35). The largest mound observed is evident from Figure 35, and it has a width of nearly 10 km, a length of more than 13 km, and a height of more than 100 ms TWT. The same mound is also revealed from Figure 32, which further shows the different nature of the mounds within SU4 in comparison to the buildups within SU3. The mounds within SU4 occur more isolated and do not have any indications of polygonal geometries.

Time structure and thickness maps

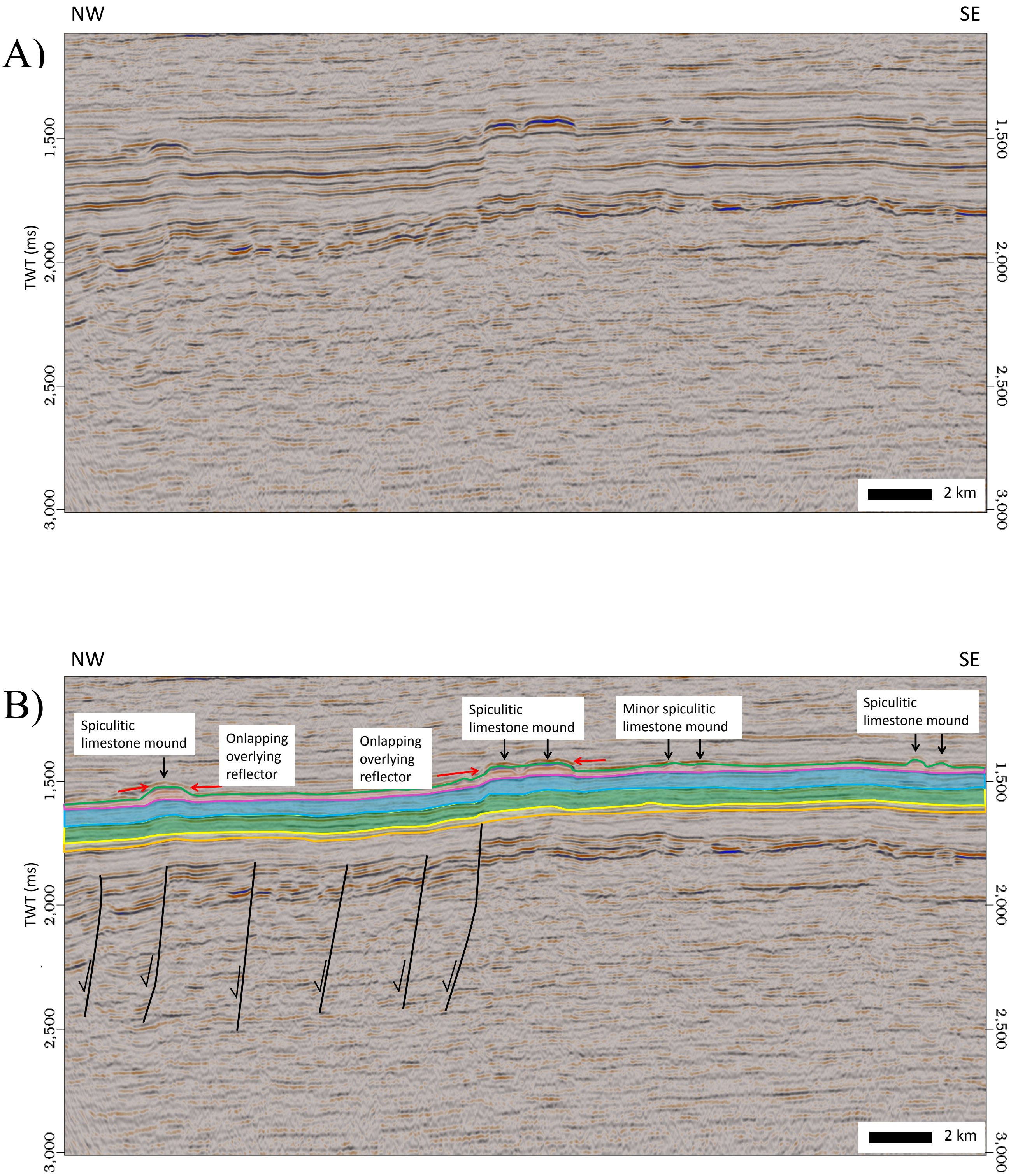
The upper boundary of SU4 (Near top Tempelfjorden horizon) has been interpreted across the entire Finnmark Platform, and a time structure map is shown in Figure 37A. This time structure map confirms the overall monocline appearance of the eastern province. No major differences can be observed between the time structure maps of the different units. On the eastern province, SU4 is affected by FF2 and FF3 (Figure 37A).

Figure 37B shows the thickness variation of SU4 across the eastern province. The unit appears thinnest in the north, and greatest in the south. On the northern parts of the platform, the unit is only around 20 ms TWT thick (e.g. Figure 25), whereas the greatest thicknesses, locally around 120 ms TWT, are observed towards the southern part where the mounds are localized (Figures 34 and 35). Elsewhere on the platform, the unit has a nearly constant thickness around 60 ms TWT (Figure 37B).

Interpretation

Well 7128/4-1 drilled the flank of one of the mounds within SU4, and thus revealed their composition of spiculitic limestone with a high content of bryozoans and echinoderms (Samuelsberg et al., 2003). Towards the northern part of the platform, in areas where these mounds have not been observed, spiculitic chert is thought to be the dominant lithology (Samuelsberg et al., 2003). This has been confirmed by the two northernmost exploration wells; 7229/11-1 and 7228/9-1S (Larssen et al., 2002). Consequently, the sharp boundary between the underlying SU3 and the overlying SU4 is thought to represent a transition from tight cold-water limestones towards dominance of spiculitic limestones and chert (Larssen et al., 2002).

The overall distribution of observed biogenic Paleozoic buildups and mounds across the Finnmark Platform is summarized in Figure 38. There is a clear difference in where the different buildups and mounds seem to favor growth. Possible reasons for this will be discussed in Chapter 5.



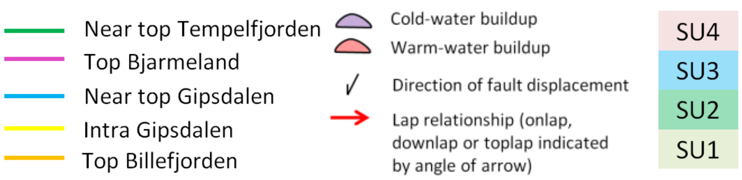


Figure 34: A) Uninterpreted and B) interpreted seismic line ST9715-406. Note the isolated spiculitic limestone mounds in various sizes. These mounds are characterized by chaotic internal signature and onlapping overlying reflectors. Vertical exaggeration 8x. See Figure 21 for location of the line.

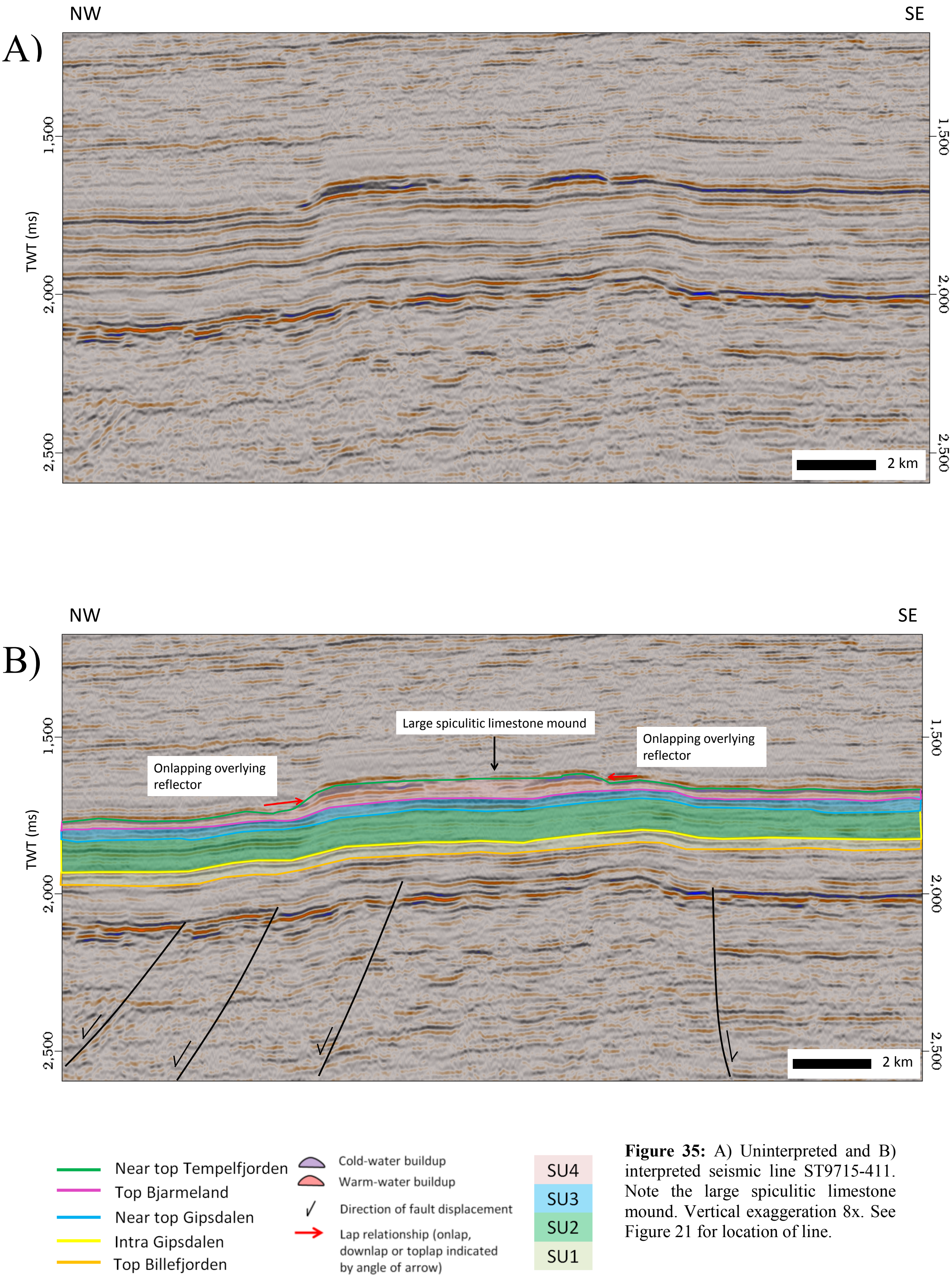


Figure 35: A) Uninterpreted and B) interpreted seismic line ST9715-411. Note the large spiculitic limestone mound. Vertical exaggeration 8x. See Figure 21 for location of line.

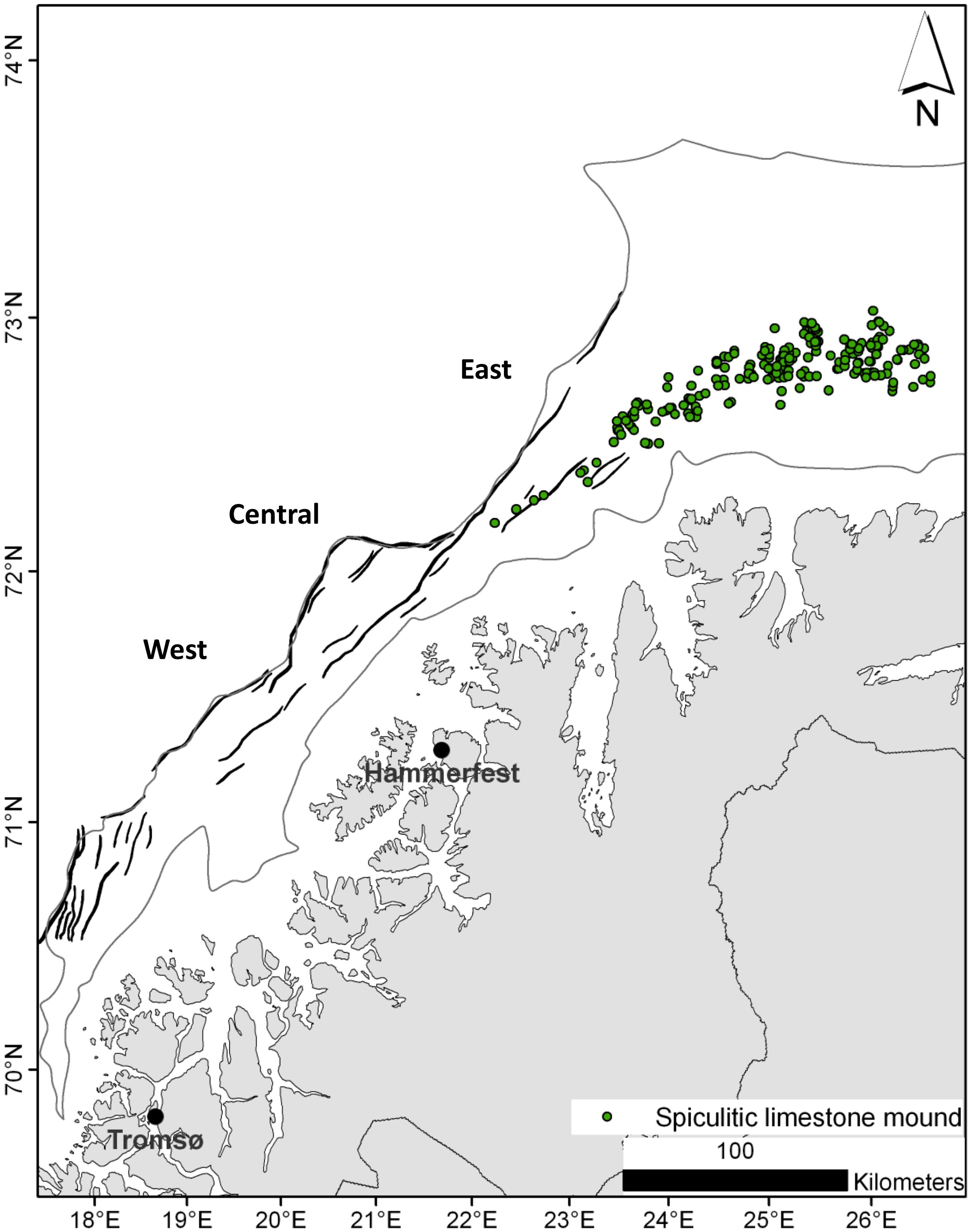
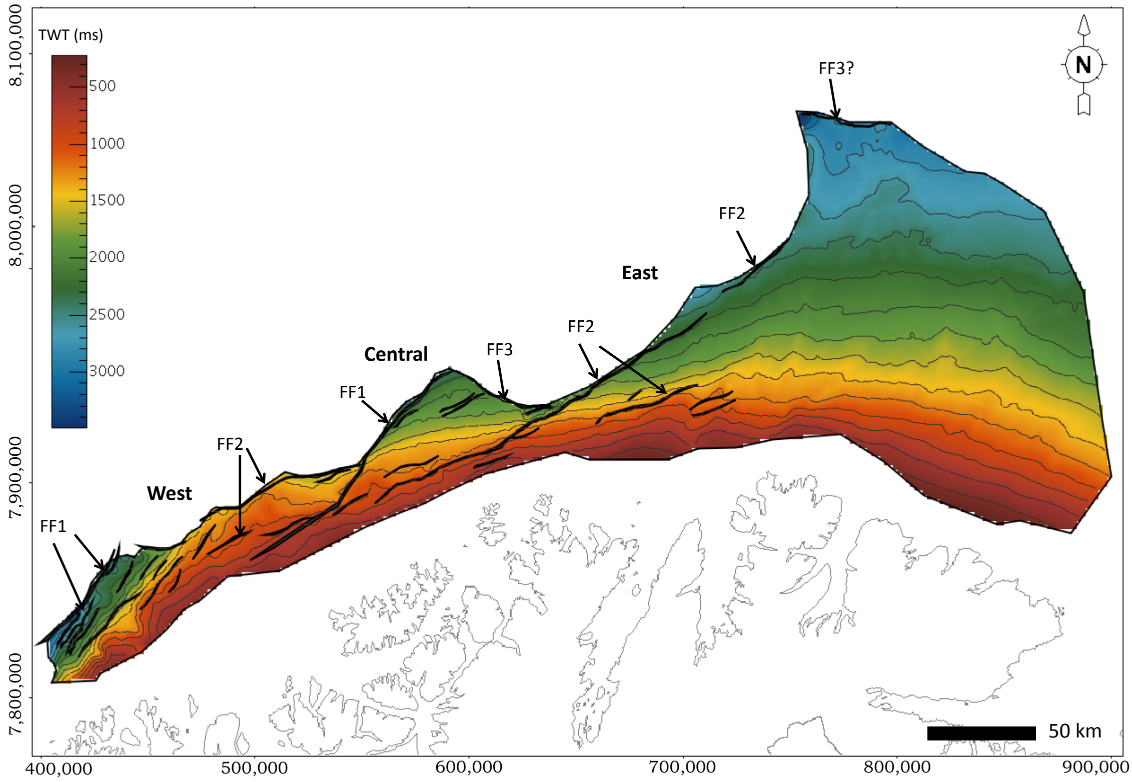


Figure 36: Observed spiculitic limestone (SU4) mounds across the Finnmark Platform. Note the clear trend in occurrence on the proximal parts of the platform.

A)



B)

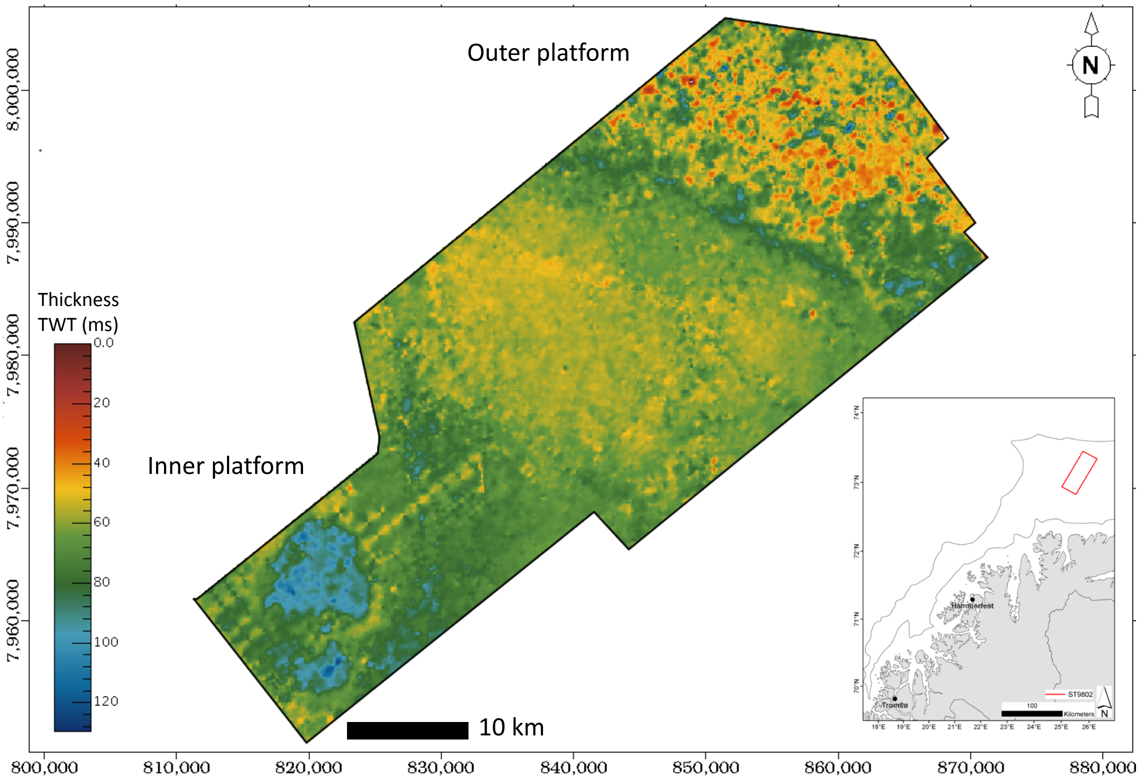


Figure 37: A) Time structure map of top SU4 (Near top Tempelfjorden horizon). The overall monocline platform geometry, as shown by the rest of the time structure maps, is confirmed. In the eastern province, SU4 is affected by FF2 and FF3. B) Time thickness map of SU4 from 3D cube ST9802. SU4 is thinnest in the distal platform areas where it appears with a thickness of approximately 20 ms TWT. Greater thicknesses, locally around 120 ms TWT, are observed on the proximal parts where the mounds are localized. Elsewhere on the platform, SU4 appears with a nearly constant thickness around 60 ms TWT. The patchy thickness variation, especially in the outer platform area, is a result of underlying evaporites, which makes a consistent interpretation challenging. The location of the 3D cube can be seen from the inset map in the lower right. Coordinate system UTM 34 ED 50.

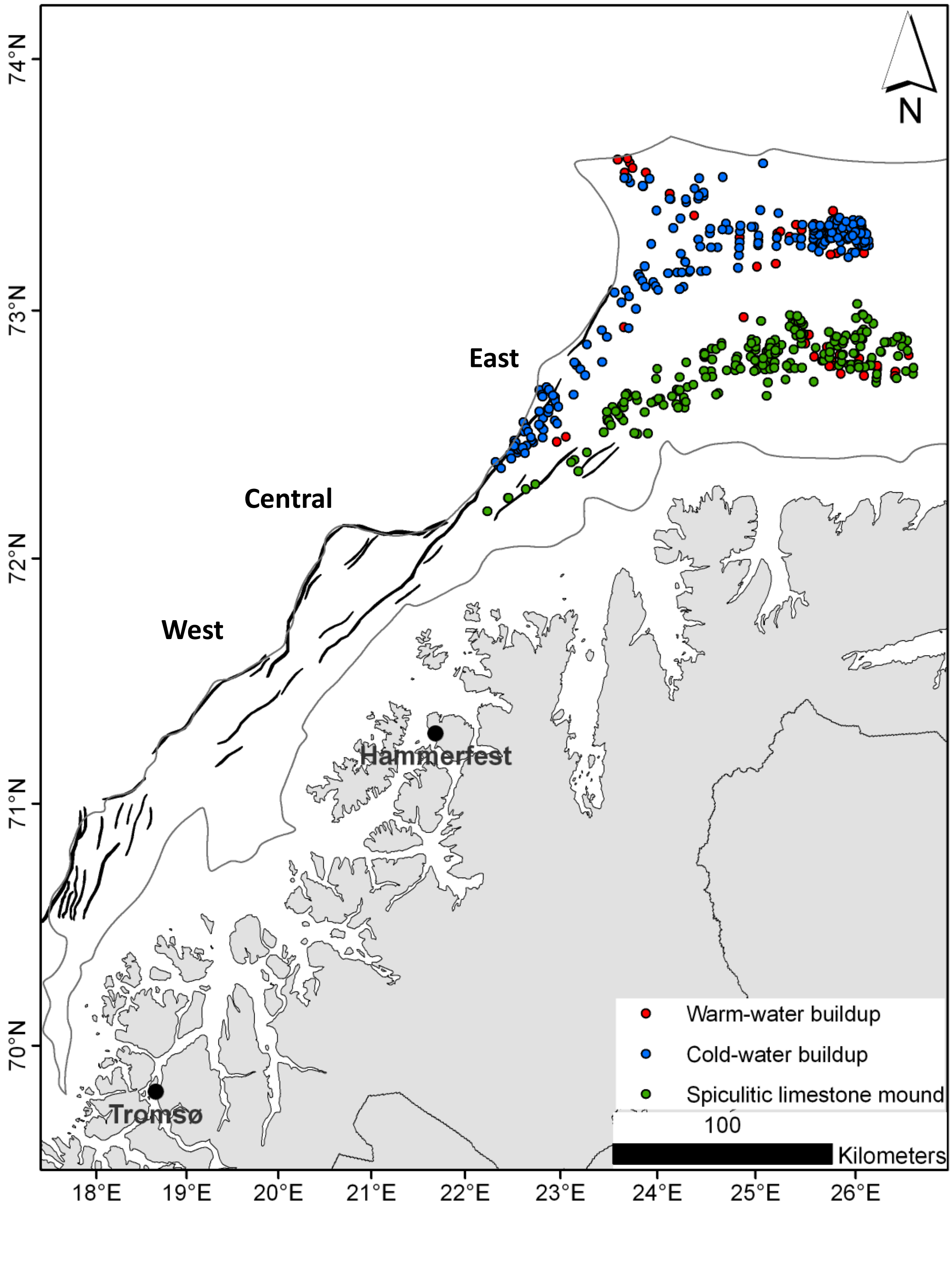


Figure 38: Overall distribution of observed Paleozoic biogenic buildups/mounds on the Finnmark Platform. The warm-water (SU1 and SU2) buildups appear randomly scattered across the eastern province. Contrastingly, the cold-water (SU3) buildups, and spiculitic limestone (SU4) mounds seem to appear in more confined areas, on the outer and inner platform respectively. See text for more details.

4.3.2 Central province

Overall, the central province of the Finnmark Platform appears more structurally complex than the eastern province (Figure 9). The overall thickness of the Upper Paleozoic biogenic interval is significantly reduced compared to in the east (Figure 11), and several of the seismic units observed in the eastern province seem to pinch-out in this area (Figure 9). No wells have drilled this province, therefore all the interpretation is based on long distance seismic correlation.

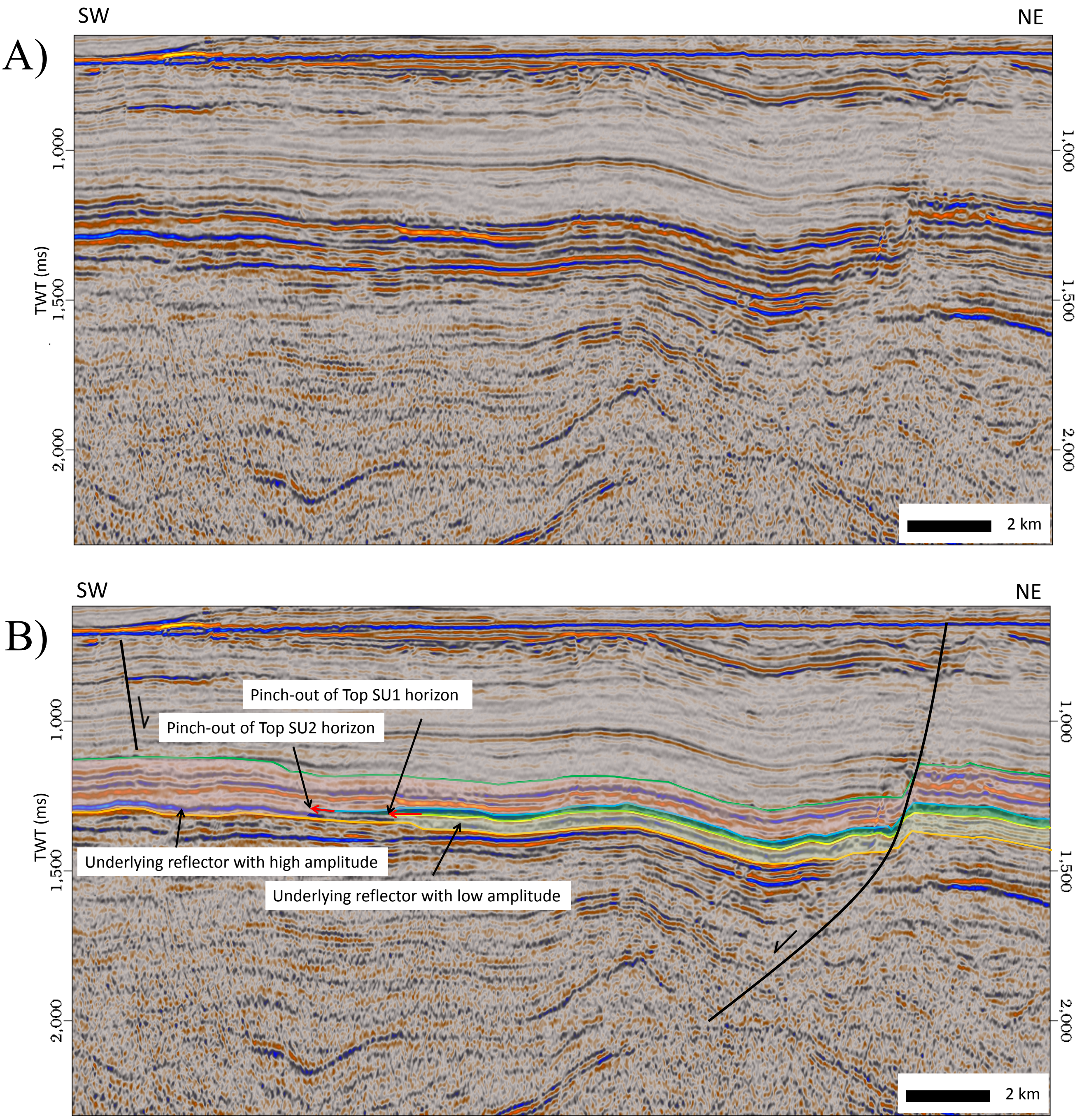
4.3.2.1 SU1 and SU2

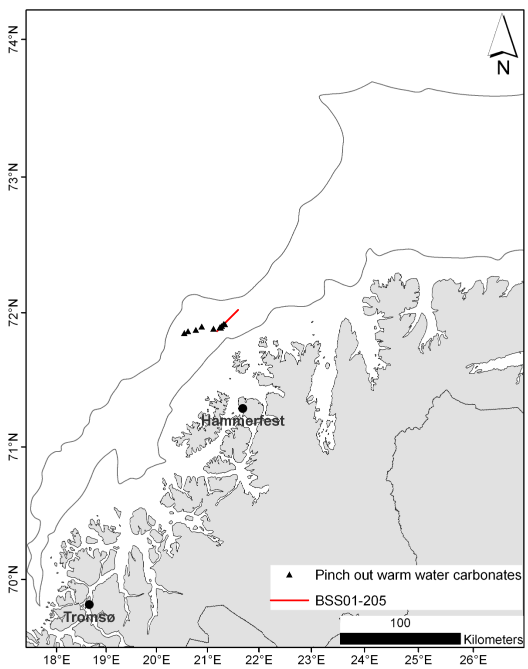
Observations

In the central province, SU1 and SU2 reveal overall similar seismic characteristics as observed in the eastern province. However, the thickness of the units and the occurrence of buildups appear highly reduced in comparison to in the east. Neither SU1 nor SU2 buildups have been observed in the central province (Figure 29). Both the upper boundary of SU1 (Intra Gipsdalen horizon) and the upper boundary of SU2 (Near top Gipsdalen horizon) are observed to pinch-out in the central province. These observations have been made on several of the seismic lines in the area (see map in Figure 39). Figure 39 shows an example of the observed gradual thinning of the units and the eventual pinch-out of the uppermost boundaries. In addition, remarkable differences in the signature of the underlying reflections on both sides of the observed pinch-out location have been observed. The reflections within SU1 are characterized by low amplitudes; while the apparent same reflector reveals significantly higher amplitude where SU1 and SU2 are interpreted as being absent. The same gradual thinning, pinch-out of the uppermost boundaries, and significant changes in amplitude of the underlying reflector can be seen from an approximately perpendicular seismic line shown in Figure 40.

Interpretation

Both SU1 and SU2 seem to pinch-out on the central province of the Finnmark Platform. These indications are supported by observed changes in amplitude of the underlying reflector, which is thought to represent a change in lithological composition. Observations of the same phenomena on several seismic lines in the area, enhances the likelihood and confident of an observed stratigraphical boundary on the central province. On the Finnmark Platform, the warm-water carbonates (SU1 and SU2) within the Gipsdalen Group probably never reached the areas west of the central province. Possible reasons for this will be discussed in Chapter 5.





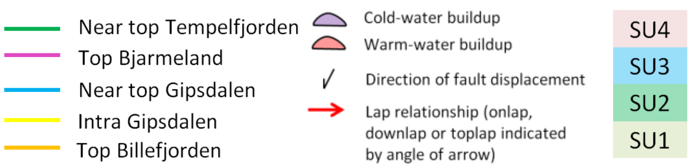
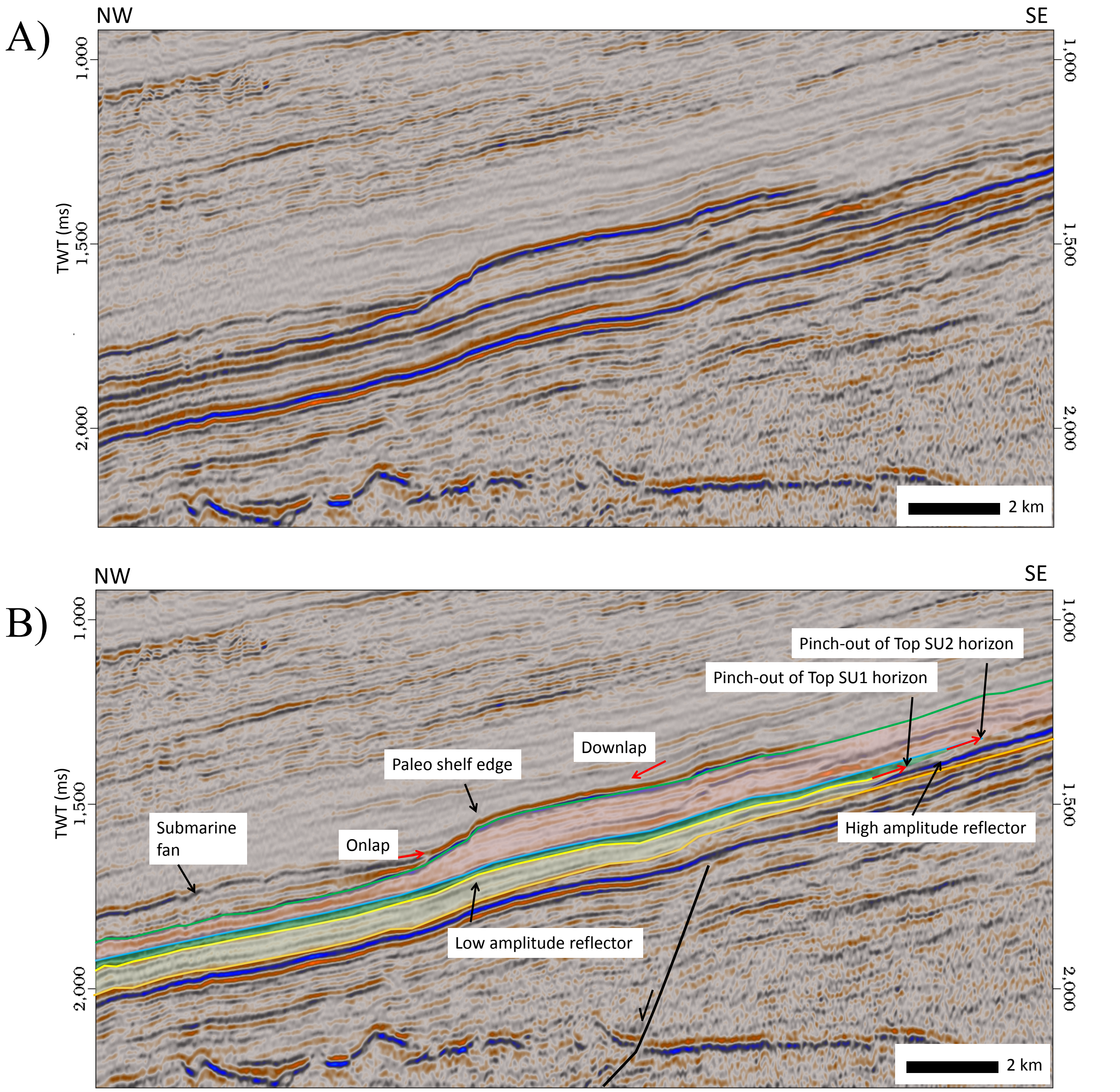
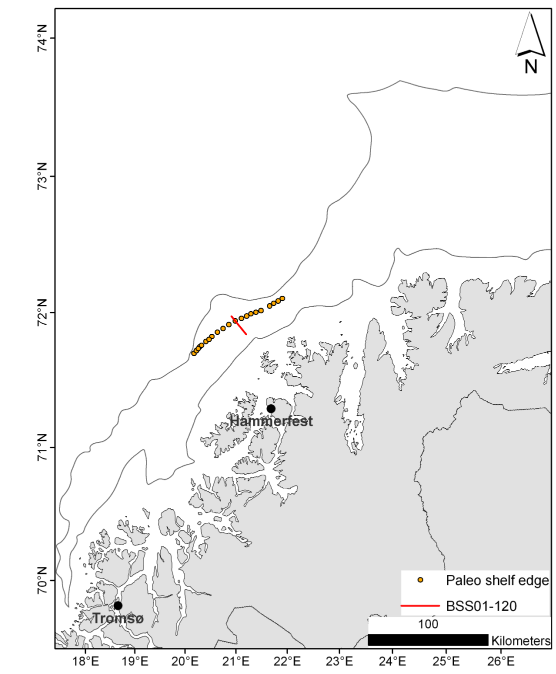


Figure 39: A) Uninterpreted and B) interpreted seismic line BSS01-205. The horizons (Intra Gipsdalen and Near top Gipsdalen) bounding the warm-water carbonates within SU2 (the Gipsdalen Group) seem to pinch-out. Clear changes in the amplitude of the underlying reflectors have also been observed in relation to this pinch-out. The pinch-out, and changing amplitude of the underlying reflectors, has been observed on several of the seismic lines in the central province, these locations are marked with a triangle on the map in the lower left corner. The location of the seismic line can be seen from the same map. Vertical exaggeration 8x.





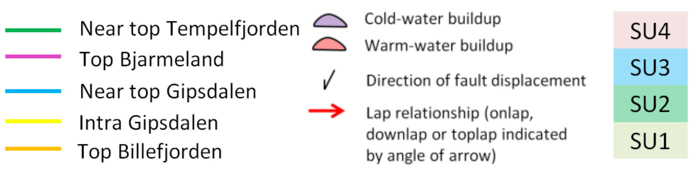


Figure 40: A) Uninterpreted and B) interpreted seismic line BSS01-120. Similar features to what was observed in Figure 39 can be seen. The horizons (Intra Gipsdalen and Near top Gipsdalen) bounding the warm-water carbonates within SU2 (the Gipsdalen Group) seem to pinch-out. Clear changes in the amplitude of the underlying reflectors can also be observed in relation to this pinch-out. A paleo shelf edge is also observed. This feature has been observed across large parts of the central province and is marked in the map in the lower left corner. Furthermore, a possible submarine fan is observed downslope of the paleo shelf edge. This fan was likely formed during a lowstand period. See text for more details. The location of the seismic line can be seen from the map in the lower left corner. Vertical exaggeration 8x.

4.3.2.2 SU3

Observations

The SU3 unit that has been observed in the eastern province reveals indications of not being present in most of the central province. The high amplitude reflector with high continuity that defines the top boundary of the unit is observed to pinch-out (Figure 41) in the transition between the eastern and central provinces. This pinch-out has been observed on several of the available seismic lines in the area (see map in Figure 41). However, it should be mentioned that there is only a limited amount of seismic lines present in this area (Figure 2). The thickness of SU3 is clearly reduced in the same area as the pinch-out of the upper boundary (Top Bjarmeland horizon) is observed (Figure 41). Although the thickness of the unit is close to the vertical resolution of the seismic, and the unit therefore possibly could appear further to the west, no indications of this have been observed. No SU3 (cold-water) buildups have been observed on the central province (Figure 31).

Interpretation

Termination of the upper boundary in combination with reduced thickness, points towards a pinch-out of the SU3 unit near the central province of the platform. This is hence the proposed explanation for the absence of cold-water carbonates on the western part of the Finnmark Platform, as indicated by the westernmost well 7120/12-4 (Norsk Hydro A/S, 1984). The seismic data indicates that the cold-water carbonates (SU3) were not deposited as far west as the underlying warm-water carbonates (SU2). Possible reasons for this will be discussed in Chapter 5.

4.3.2.3 SU4

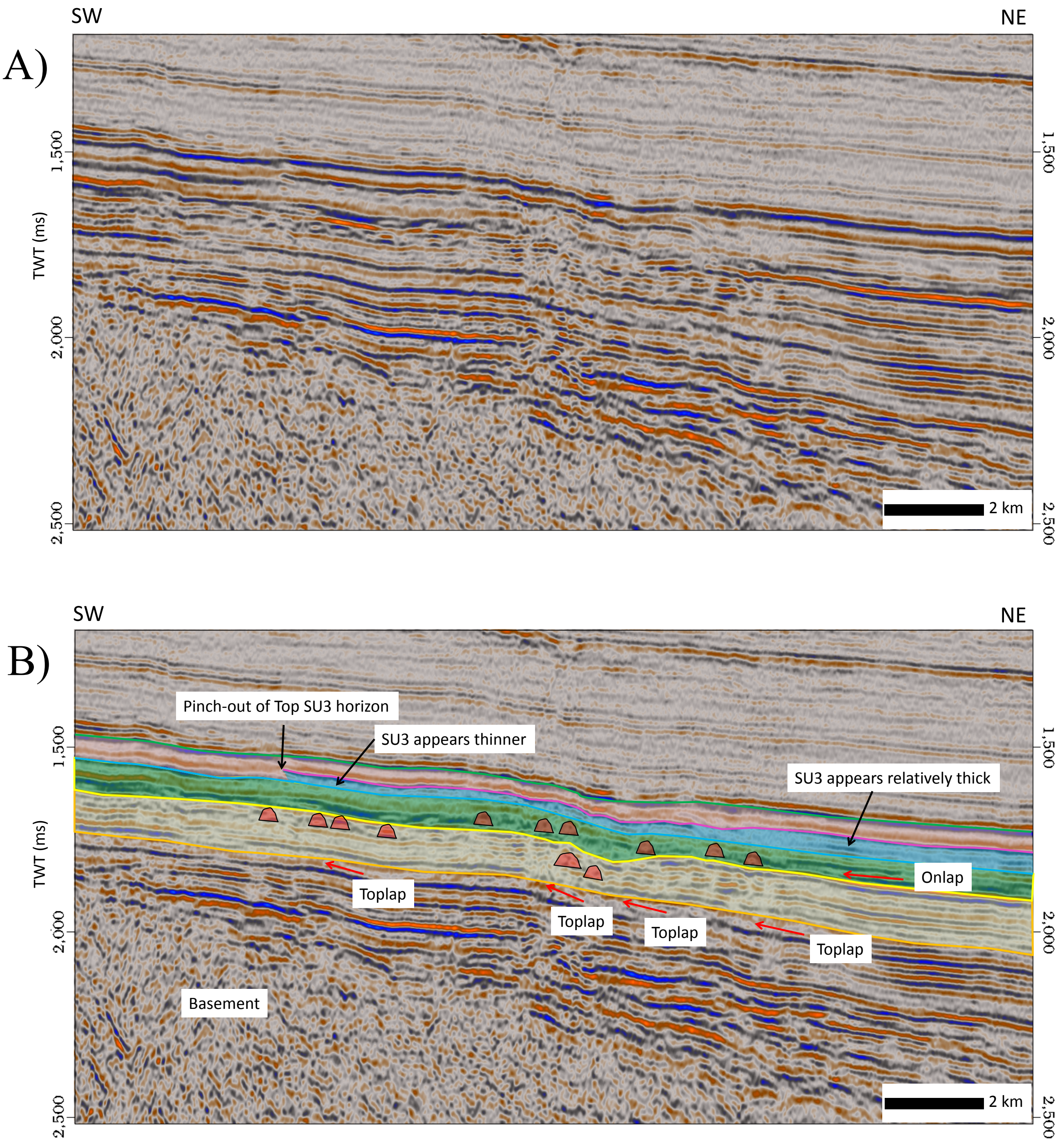
Observations

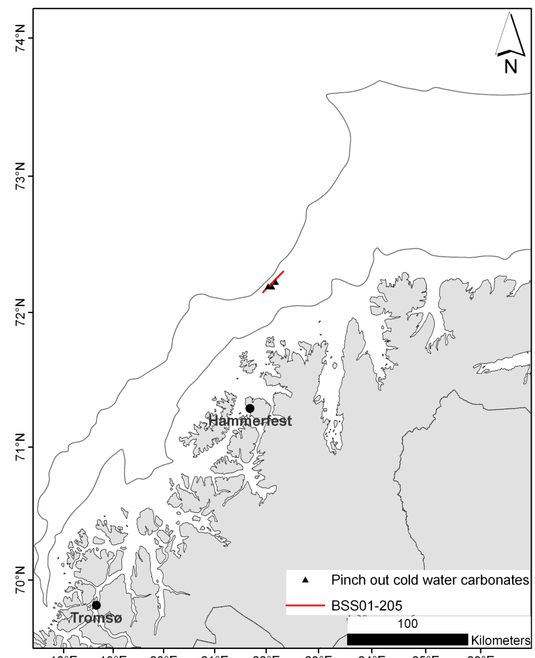
While the three stratigraphically underlying units are observed to pinch-out near the central province, SU4 appears with an overall increased thickness (Figures 39, 40 and 41). Continuous higher amplitude reflections occur in combination with less continuous lower amplitude reflections. In the central province of the Finnmark Platform, no mounded features have been observed within SU4 (Figure 36). However, another eye-catching feature has been observed. On dip sections, the high amplitude and continuous reflector defining the uppermost boundary of the unit (Near top Tempelfjorden horizon), reveals a clear offlap break (Figure 40). Stratigraphically overlying reflections are observed to downlap and onlap the top surface (Figure 40). The internal reflection pattern is characterized by low amplitude reflections with relatively low continuity (Figure 40). On strike sections, it reveals a broad lense-shaped external form. The observed stratigraphical feature appears highly continuous, as it can be observed across a distance of nearly 70 km (see map in Figure 40). A fan-shaped feature characterized by medium amplitude reflections is observed onlapping in the depositional down-dip direction (Figure 40).

Interpretation

The spiculitic deposits appear more dominant on the central province, as the underlying carbonate units seem to pinch-out. The observed increase in amplitude of the underlying reflectors related to pinch-out of the Intra Gipsdalen and Near top Gipsdalen horizons, are hence thought to represent a change from dominance of carbonates towards spiculitic deposits.

The characteristic stratigraphical feature observed within SU4 is thought to represent a paleo shelf edge. No clear indications of progradation of this shelf edge have been observed. Consequently, it was likely formed under relatively stable conditions. The fan-shaped feature is thought to represent a sub-marine fan that was formed during a period of low relative sea level. The development of both the paleo shelf edge and the sub-marine fan will be further discussed in Chapter 5.





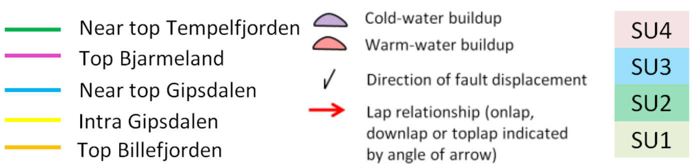


Figure 41: A) Uninterpreted and B) interpreted seismic line BSS01-205. Termination of the upper boundary of SU3 (Top Bjarmeland horizon) in combination with reduced thickness of the unit indicates a pinch-out of the cold-water carbonates (SU3) in the transition between the eastern and central provinces. Locations where this pinch-out has been observed are marked with triangles on the map in the lower left corner. The location of the seismic line can be seen from the same map. Vertical exaggeration 8x.

4.3.3 Western province

Based on well 7120/12-4, the western province of the Finnmark Platform is more clastic dominated than any of the other provinces (Figures 7 and 8). Only three of the five horizons interpreted on the eastern province can be observed, resulting in presence of only two of the seismic units, SU1 and SU4 (Figures 7 and 8). A summary of the main characteristics of the observed seismic units on the western province is given in Table 7.

4.3.3.1 SU1

Observation

Well 7120/12-4 encountered 84 meters of the Ugle Formation, containing sediments of non-marine origin (Larssen et al., 2002). The interpreted basal reflector of SU1 is characterized by lower amplitude, as the difference in acoustic impedance between the overlying and underlying sediments are reduced, compared to in the east. Consequently, it is also more challenging to identify. The upper boundary of SU1 is interpreted as a trough (Figure 8), which is represented by a medium amplitude reflection of medium to low continuity. SU1 is characterized by relatively low gamma-ray readings, and the top of the unit is defined where there seems to be an overall trend towards higher gamma-ray readings (Figure 8). Internally, SU1 is characterized by discontinuous low to medium amplitude reflections (Table 7). Low continuity of the bounding reflectors combined with similar seismic appearance as the overlying siliciclastics within SU4 (Table 7), made identification and interpretation of SU1 challenging in the western province. However, the observations support the previously reported local development of the Ugle Formation on the Finnmark Platform (Larssen et al., 2002).

Interpretation

The sediments that were encountered in well 7120/12-4 were mainly composed of red-brown mottled sandy siltstones in combination with grey-green calcareous nodules (Larssen et al., 2002). This lithological composition is thought to be representative for the observed localized units of SU1 on the western province of the Finnmark Platform. In comparison to the sediments of the Ugle Formation which were encountered in the shallow core 7029/03-U-02 (see Figure 2 for location), the sediments within 7120/12-4 were reported as more fine-grained (Larssen et al., 2002). This might indicate a more distal location for the western well 7120/12-4 compared to the eastern shallow core 7029/03-U-02. Possible origin of these sediments will be further discussed in Chapter 5.

4.3.3.2 SU4

Observation

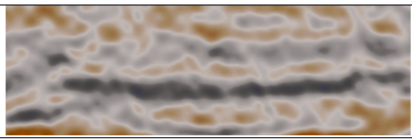
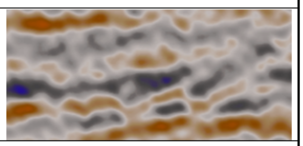
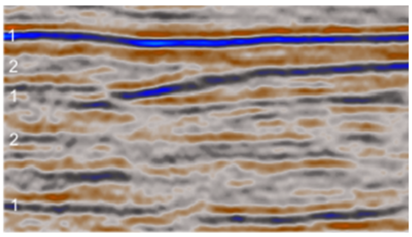
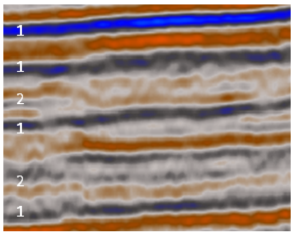
The upper boundary of SU4 is interpreted as a peak (Figure 8), represented by a high amplitude reflector with high continuity, similar to on the eastern province. The internal characteristics appear, on the other hand, quite different. On the western province, the internal character of SU4 is represented by interfingering of medium to low amplitude discontinuous to chaotic reflections, and medium to high amplitude reflections with medium to low continuity (Table 7). No mounded features have been observed (Figure 36). In addition, SU4 occurs significantly thicker in the west compared to in the east (Figures 7 and 8). Well 7120/12-4 encountered in excess of 750 meter of strata associated to SU4 (Norsk Hydro A/S, 1984; Larssen et al., 2002). On the western province, the gamma-ray log response of SU4 is predominantly characterized by relatively low readings; however there are sections which reveal significantly higher readings (Figures 7 and 8).

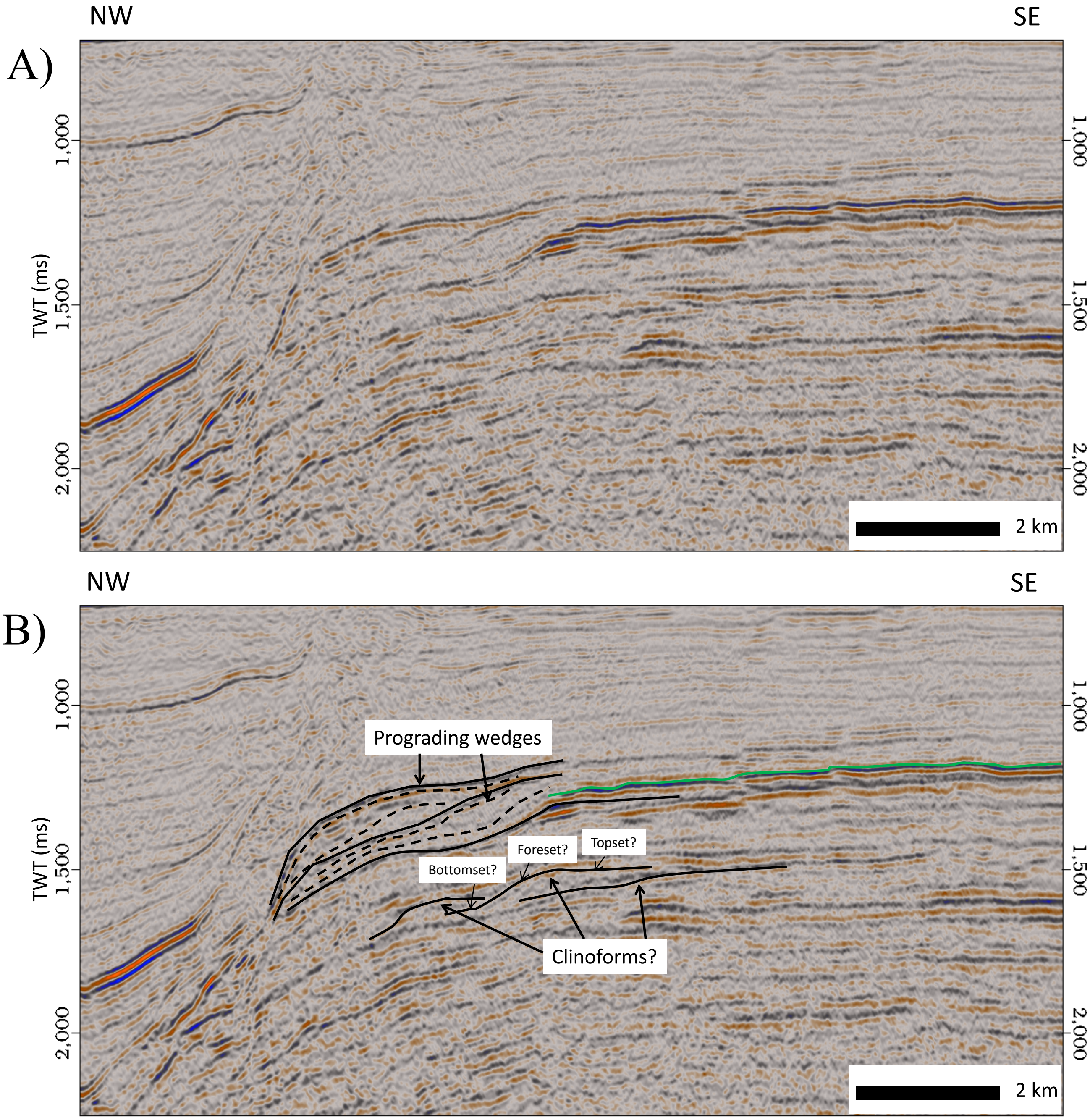
On the western province, the most eye-catching phenomenon observed within SU4 is of stratigraphic origin, and has been observed near the edge of the platform. This feature appears relatively continuous as it can be identified across a distance of more than 40 km (see map in Figure 42). In this area, several superposed packages with different sizes and shapes have been observed (Figure 42). These packages are thought to represent generations of prograding wedges, allowing for laterally displacement of successively younger wedges in what appear as the depositional downdip direction (Figure 42). Sigmoidal internal structures, possibly representing clinoforms, can be observed within the wedges (Figure 42). The sigmoidal shaped clinoforms display characteristic thin and gently dipping lower and upper segments, while the dipping middle segment appears thicker (Figure 42). Consequently, topsets, foresets, and bottomsets, with their characteristic varying gradients, in combination with a seaward advance of the offlap break, seem to be present (Figure 42). Internally, seismic reflections appear truncated, and detailed inspection also reveals several downlap and onlap relationships. All the observed clinoforms reveal a down-stepping pattern (Figure 42). The same stratigraphic phenomenon can also be spotted near the edge of the platform in Figure 16.

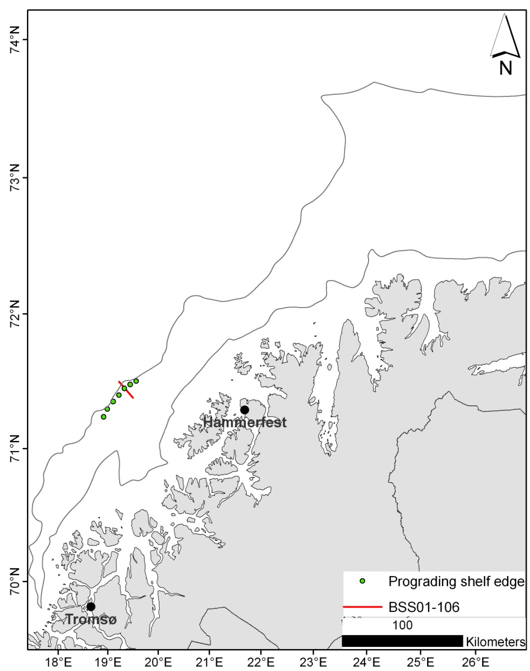
Interpretation

The observed occurrence of higher amplitude and continuous reflectors, in combination with lower amplitude chaotic reflection pattern, is thought to represent interfingering of spiculites and siliciclastics (Table 7). This is also supported by the strata penetrated in well 7120/12-4 (Norsk Hydro A/S, 1984; Larssen et al., 2002). These observations point towards competing biogenic and siliciclastic dominated environments at the time of deposition. A transition from silicified fine-grained siliciclastics to limestone is reflected by a marked decrease in both density and gamma-ray response (Figures 7 and 8) (Larssen et al., 2002). The observed characteristic stratigraphic feature near the edge of the platform, is likely representing progradation of a paleo shelf edge. Increased sediment supply, in combination with lowered sea level, possibly initiated the observed progradation. Relative sea level fluctuations might have been the controlling mechanism responsible for transition between shallow-marine biogenic and siliciclastic dominated environments. This will be further discussed in the following chapter.

Table 7: Seismic characteristics of the observed units in the western province.

	Seismic reflection characteristics	Interpretation	Examples	
SU1	Discontinuous, chaotic low to medium amplitude reflections	Sandy siltstones		
SU4	High amplitude, continuous reflector bounding an interval characterized by interfingering of medium-low amplitude discontinuous to chaotic reflections, and medium-high amplitude reflections with medium to low continuity.	Interfingering of spiculites (1) and siliciclastics (2).		





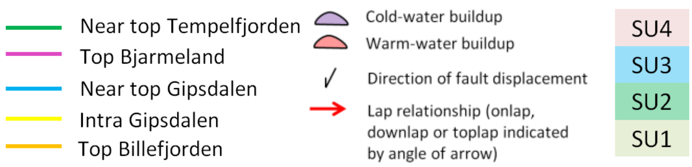


Figure 42: A) Uninterpreted and B) interpreted seismic line BSS01-106. Prograding wedges are observed near the platform edge. Sigmoidal internal structures, possibly representing clinoforms, can be observed within the wedges. All the observed clinoforms reveal a down-stepping pattern suggesting deposition during periods of low relative sea level. See text for more details. In the western province, this feature has been observed over a distance of more than 40 km (marked on the map in the lower left corner). The location of the seismic line is shown in the same map. Vertical exaggeration 5x.

Chapter 5: Discussion

5.1 Timing and processes controlling fault evolution

Interpretation of the study area revealed major differences in the structural complexity between the western and eastern part of the Finnmark Platform. The western platform is clearly affected by significant Mesozoic and Cenozoic deformation, whereas the eastern platform seems to have behaved as a relatively stable platform with less pronounced tectonic activity since Late Carboniferous times (Gabrielsen et al., 1990).

The major FF1 fault, which separates the western from the central province (Figures 12 and 13), indicates activity during Middle to Late Permian times as significant increase in thickness of the succession is observed (Figure 11). Several of the other NNE-SSW striking faults assigned to FF1 support activity during the latter half of Permian, although varying throw measurements have been observed (Figures 15 and 16). Middle to Late Permian activity of NNE-SSW trending faults is however not supported by the E-W regional stress orientation, which has been reported for the Late Paleozoic times (Ziegler, 1989; Mosar et al., 2002). Despite this, the observations coincide with a detailed structural analysis of the Troms-Finnmark Fault Complex compiled by Ahmed (2012). He performed an "Expansion Index" analysis, which also indicated growth of strata belonging to this age. Consequently, he proposed a WNW-ESE local stress orientation during initial stages of rifting in the Late Paleozoic. Based on this, a WNW-ESE oriented σ_3 during the latter half of Permian is thought to represent the origin of the observed NNE-SSW trending faults assigned to FF1.

Although affecting the Upper Paleozoic succession, the NE-SW striking faults assigned to FF2, do not reveal any sign of Late Paleozoic activity (Figures 16, 17, 18 and 19). Thus, the faults of FF2 appear younger in age compared to the faults of FF1. During the Late Cretaceous, Mosar et al. (2002) reported a change towards a NW-NNW opening direction between the present-day Norwegian shelf and East Greenland. This indicates that a suitable orientation of the regional stress regime, to form the NE-SW striking faults of FF2, might have existed during Late Cretaceous times. Consequently, formation of FF2 was likely initiated during the Late Cretaceous, followed by subsequent stages of reactivation, as indicated by the seismic data (Figures 16 and 17).

The observed WNW-ESE striking fault of FF3 on the central Finnmark Platform (Figure 12), is probably representing an offshore extension of the Trollfjord-Komagelv Fault Zone (see Figure 3 for location) (Gabrielsen, 1984). This fault zone comprises strike-slip faults from which dextral megashear in the order of 500-1000 km has been reported (Kjøde et al., 1978; Gabrielsen, 1984; Rice et al., 1989). Gabrielsen (1984) reported pre-Caledonian activity, with subsequent late- or post-Caledonian reactivation, whereas Rice et al. (1989) suggested fault movement intimately associated with Late Caledonian thrusting. Regardless of the discrepancies, the fault assigned to FF3 was likely active pre-deposition of the Upper Paleozoic succession on the Finnmark Platform.

In the Barents Sea, rifting has been reported from the latest Serpukhovian times, and overall the Bashkirian was characterized by formation, and infilling of tilted half-graben systems (Gjelberg and Steel, 1983; Steel and Worsley, 1984; Johannessen and Steel, 1992). The NE-SW striking faults of FF4 have been observed bounding tilted half-graben systems (Figure 20) in the eastern province of the Finnmark Platform (Figure 12), and are consequently thought to originate from this regional late Serpukhovian rifting event.

5.2 Depositional evolution

Based on the stratigraphic and structural observations from this study, a proposed Late Paleozoic paleogeographic reconstruction of the Finnmark Platform is presented in Figure 43. Overall, the evolution of the eastern Finnmark Platform resembles that previously reported by other authors (e.g. Bugge et al., 1995; Samuelsberg et al., 2003; Stemmerik and Worsley, 2005; Colpaert et al., 2007; Rafaelsen et al., 2008). However, new information about the depositional evolution of the central and western Finnmark Platform will be proposed.

5.2.1 Late Serpukhovian – Bashkirian (early SU1) local sedimentation

During late Serpukhovian and Bashkirian times, most of the Finnmark Platform was part of the Baltic Shield, and only local sedimentation took place (Figure 43A). Red-colored alluvial sediments, characteristic of the Ugle Formation, have been encountered by exploration well 7120/12-4 on the western platform, and in shallow core 7029/03-U-02 on the eastern platform (see Figure 2 for location), suggesting localized occurrence of arid alluvial fan systems. Larssen et al. (2002) suggested alluvial fans building out from active faults, however no active faults from the given time interval have been observed on the western part of the platform. The faults observed on the western Finnmark Platform appear to be of Middle to Late Permian (FF1) and Late Cretaceous (FF2) origin. Consequently, relatively small scale alluvial fans are rather thought to have been sourced from the adjacent hinterland, resulting in localized deposition of siliciclastic sediments on the platform (Figure 43A). The coarser-grained sediments encountered in the east likely represent proximal parts of an alluvial fan, whereas the finer-grained sediments in the west represent down-stream flood-plain sediments. This might indicate presence of highlands with quite high relief in the northern parts of Norway at this time.

5.2.2 Late Bashkirian – Kasimovian (late SU1) marine incursion

During the late Bashkirian to Kasimovian times, a progressive marine incursion from the east took place. The eastern province was gradually flooded, and more widespread sedimentation resumed (Bugge et al., 1995) as a shallow-water shelf environment with mixed siliciclastic and carbonate deposition evolved (Figure 43B). Initially, the shoreface areas were sand-dominated, while the finer-grained sediments accumulated more distally, resulting in silt-dominated offshore areas (Larssen et al., 2002). The overall rise in relative sea level proceeded, and eventually the entire eastern, and partly the central provinces were flooded (Figure 43B). As a result, the upper part of SU1 comprises fine-grained siliciclastics sourced from the Norwegian mainland in the proximal platform areas, while subtidal carbonates dominate the more distal parts of the platform (Larssen et al., 2002). Overall, well data from the eastern province reveals an upward transition of lithofacies, going from dominance of siliciclastics, to mixed siliciclastics and carbonates, and eventually to carbonates. This transition is thought to reflect the continuing effects of the regional transgression occurring at the time (Worsley et al., 2001). Diachronous drowning of the siliciclastic provenance areas took place simultaneously as favorable conditions for carbonate deposition, and buildup development, were established across progressively larger parts of the distal platform areas in the east. The varying lithofacies within SU1 is a response to the high frequency and high amplitude eustatic sea level fluctuations, associated with the icehouse conditions that prevailed at the time (Ehrenberg et al., 1998; Stemmerik et al., 1999; Stemmerik, 2000; Stemmerik and Worsley, 2005; Worsley, 2008). During Late Carboniferous times, the western, and also parts of the central provinces of the Finnmark Platform are thought to have been a positive feature (Figures 43A and 43B). As a result, the marine incursion never reached, and submerged, these areas.

5.2.3 Gzhelian - Asselian (SU2) shallow warm-water carbonate platform

The overall relative sea level rise continued, thereupon also continuing the gradual drowning of the siliciclastic provenance areas. Consequently, the clastic input decreased, and by the early Gzhelian times, a shallow warm-water carbonate shelf covered the eastern Finnmark Platform (Figure 43C) (Stemmerik and Worsley, 2005). The seismic data indicates that an inner-middle shelf environment with scattered organic buildups developed in the east, while parts of the central, and the western, platform remained subaerially exposed (Figure

43C). Deposition on the central platform areas was thus characterized by onlap of the positive and still emergent areas to the west. The scattered distribution of warm-water carbonate buildups (Figure 29) likely indicates that the optimum zone for carbonate buildup development, with the favorable depth window, repeatedly shifted across the entire eastern province. Consequently, buildup initiation and growth was facilitated at different locations over the eastern platform at various times. Well and core data, supplemented with seismic data, reveal that the ice house world had pronounced impact on the eastern platform at this time. Cycles of outer shelf foraminifera-, algal-, fusulinid- and crinoid-rich packstones and wackestone, bounded by subaerial exposure surfaces, have been reported from the Late Carboniferous carbonate platform (Stemmerik and Worsley, 2005). Several phases of relative lowering of the sea level resulted in prolonged periods of subaerial exposure of the shelf carbonates (Figure 43D) (Henriksen et al., 2011). Thin evaporite layers were deposited in local sub-basins on the proximal parts of the platform (Samuelsberg et al., 2003), while the seismic data indicate that the outer platform areas remained submerged for longer periods, resulting in deposition of relatively thick evaporite successions (Figures 22, 24, 25, 28 and 43D) (Samuelsberg et al., 2003).

5.2.4 Early Sakmarian (late SU2- early SU3) flooding

In the early Sakmarian times, a regional flooding event occurred, recording a significant shift in depositional conditions across the central Pangean shelf (Stemmerik and Worsley, 2005). This abrupt shift might be related to the development of the Uralides, which possibly affected the oceanographic circulation patterns (Stemmerik and Worsley, 2005; Henriksen et al., 2011). The tropical-subtropical cyclic, exposure-capped warm-water carbonate deposits of SU2 were replaced (Ehrenberg et al., 1998; Stemmerik, 2000) by deeper shelf foraminifera- and crinoid-rich wackestones and shales (Stemmerik and Worsley, 2005), characteristic of the lower SU3 unit. In shallow core 7129/10-U-02 (see Figure 2 for location), the same flooding event is recorded as a succession of fine-grained siliciclastics (Bugge et al., 1995; Ehrenberg et al., 2001). Overall absence of exposure surfaces and evaporite deposits (Stemmerik and Worsley, 2005) indicate that SU3 was deposited at a time interval characterized by less pronounced sea level fluctuations.

5.2.5 Sakmarian-Artinskian (SU3) cool-water carbonate platform and marginal uplift

During Sakmarian to Artinskian times, a temperate cool-water platform developed across the eastern Finnmark Platform (Figure 43E) (Stemmerik, 1997; Samuelsberg et al., 2003; Henriksen et al., 2011). Cool-water shelf carbonates dominated the proximal parts of the eastern Finnmark Platform, while favorable conditions for development of bryozoan-*Tubiphytes* buildups prevailed along the eastern platform margins (Figures 31 and 43E) (Stemmerik and Worsley, 2005; Henriksen et al., 2011). The central and western parts of the platform, on the other hand, were probably still subaerially exposed (Figure 43E). Seismic data indicate that the cold-water (SU3) carbonate succession was not deposited as far west as the underlying SU2 warm-water carbonate succession. The proposed responsible mechanisms are Early Permian uplift of the marginal highland areas combined with progressive northward tilting of the Finnmark Platform, thus obstructing further westward marine incursion. Uplift of the southern and western hinterland areas is supported by reported breaks in sedimentation and condensation from the shallow cores on the most proximal parts of the Finnmark Platform (Bugge et al., 1995; Ehrenberg et al., 2001). In comparison, a regional uplift event of marginal shelfal areas and structural highs has been proposed as being responsible for the absence of Upper Sakmarian-Lower Artinskian cold-water sediments on Bjørnøya and in most of North Greenland (Worsley et al., 2001; Stemmerik and Worsley, 2005). This indicates that similar depositional settings, influenced by uplift of marginal shelfal areas and structural highs, might have occurred on Bjørnøya and on the central and western parts of the Finnmark Platform during Early Permian times.

Seismic data indicates a significant increased size of the cold-water (SU3) buildups in comparison to the warm-water (SU1 and SU2) buildups (Figures 23, 24 and 28), and this, in combination with the reported inner platform facies, indicates a pronounced deepening of the eastern Finnmark Platform from the mid-Permian times (Samuelsberg et al., 2003). The cold-water buildups appear with restricted occurrence to narrow belts along the outer parts of the platform (Figure 31), contrasting the scattered warm-water buildups (Figure 29). The large polygonal buildups observed downdip on the platform (Figure 32) have been reported as being composed by bryozoans and submarine cement (Stemmerik, 1997; Henriksen et al., 2011), and similar polygonal growth pattern have also been reported from the Loppa High (Elvebakk et al., 2002). On the Loppa High, the polygonal buildups were found to be affected by the sea floor bathymetry, controlled by underlying faults and older underlying buildups (Elvebakk et al., 2002). Similarly, on the eastern Finnmark Platform, NW-SE trending basement involved faults (as observed in Figure 32), in addition to the observed NE-SW trending faults assigned to FF4 (Figure 12), might be the controlling mechanisms for the localized occurrence of cold-water buildups in belts oriented in similar directions (Figure 31).

5.2.6 Kungurian (early SU4) flooding

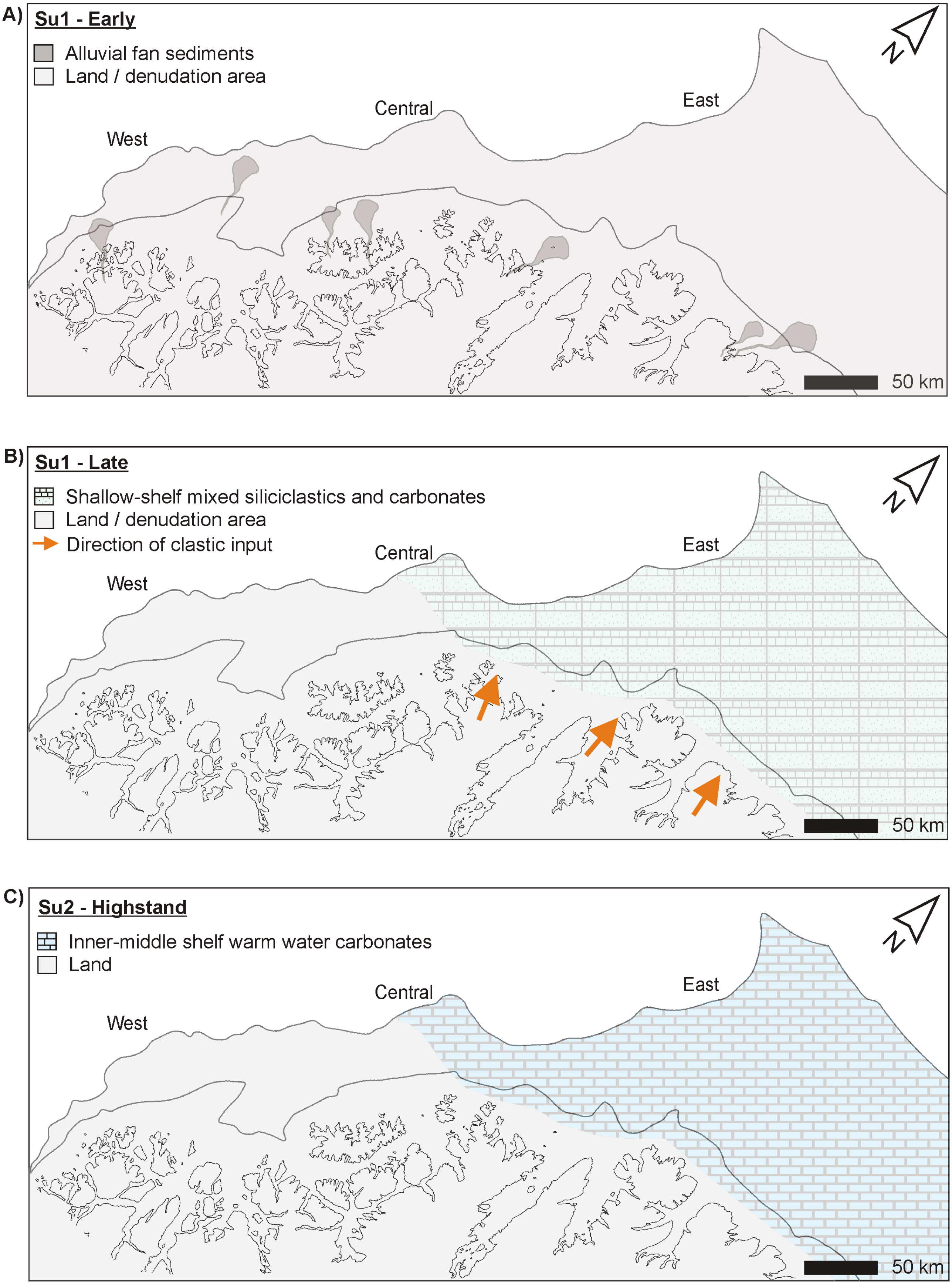
In the Kungurian times, a regional flooding event resulted in deposition of spiculites over the eastern Finnmark Platform (Figure 43F) (Stemmerik and Worsley, 2005). The outer platform areas were dominated by deposition of spiculitic chert, while spiculitic limestone developed on the inner platform areas (Samuelsberg et al., 2003; Stemmerik and Worsley, 2005). As a result of the flooding event, the cold-water (SU3) buildups drowned, and the site of favorable carbonate buildup development shifted southwards to the central parts of the platform (Figures 38 and 43F) (Samuelsberg et al., 2003).

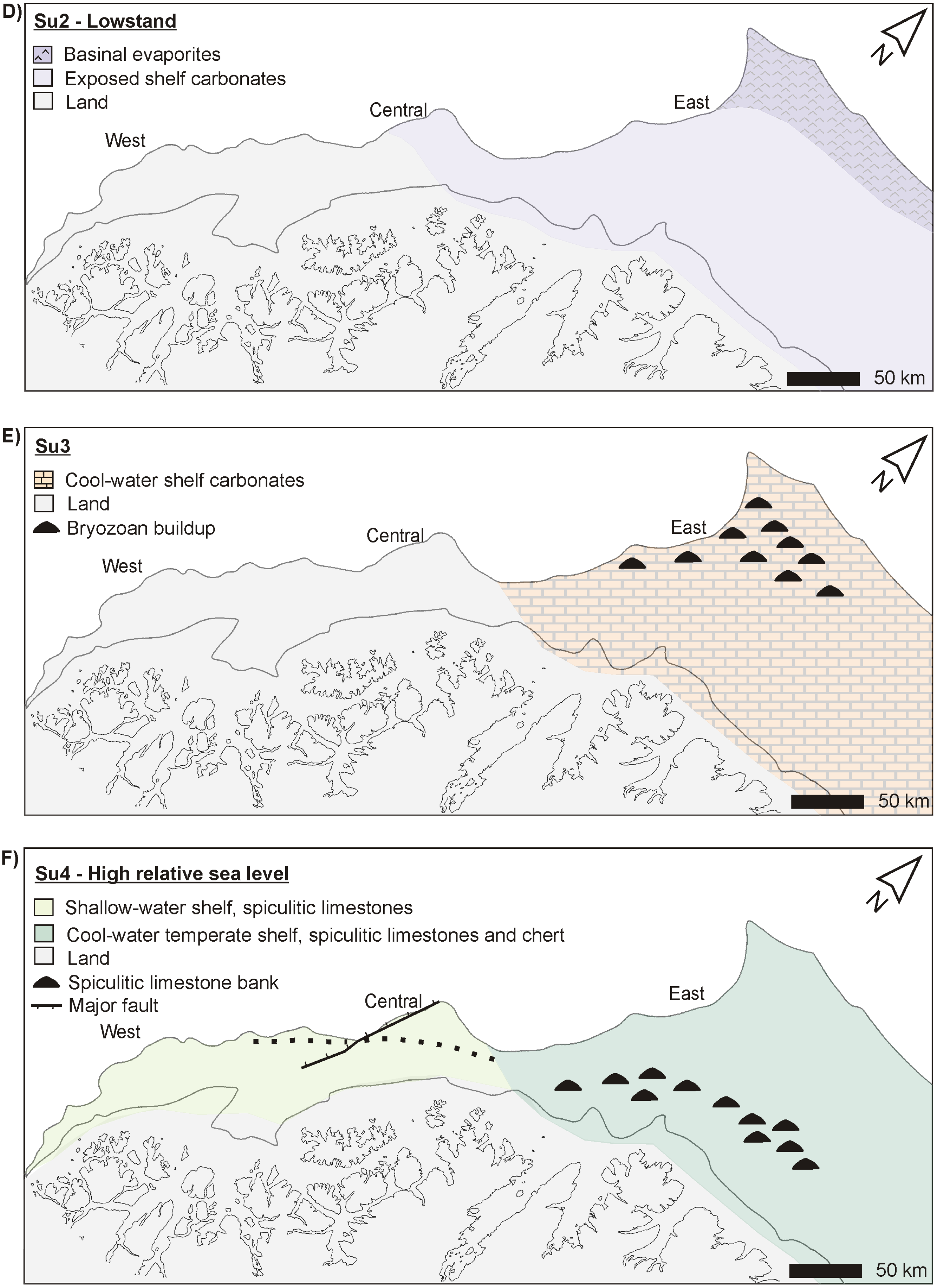
Well and seismic data reveal significant differences between the latest Permian succession in the eastern and central/western provinces, indicating various depositional settings across the Finnmark Platform at the time (Figures 43F and 43G). Overall, deeper and colder water deposition dominated the eastern Finnmark Platform (Figures 43F and 43G) (Larssen et al., 2002; Stemmerik and Worsley, 2005). However, the various facies reported (calcareous shale, limestone, and spiculite) (Larssen et al., 2002; Samuelsberg et al., 2003; Stemmerik and Worsley, 2005) are thought to indicate that deposition occurred over a range of water depths. Favorable conditions related to water depth, nutrient supply, and/or sea bed morphology are also thought to be the underlying controlling factors responsible for development of the spiculitic carbonate-dominated banks in the east-west oriented belt on the central part of the eastern platform (Figures 36, 43F and 43G). These banks were likely formed during a period of rising relative sea level, and the growth probably terminated as the sea level continued rising and eventually drowned the carbonate banks (Samuelsberg et al., 2003). The increased relative sea level in the latest Permian, probably led to an abrupt termination of the biogenic sedimentation on the eastern Finnmark Platform (Samuelsberg et al., 2003).

During the Middle to Late Permian times, western and central parts of the Finnmark Platform reveal evidences of shallower water depositional systems (Figure 43F). This appears to be the first time during the Late Paleozoic that marine environments reached and submerged the central and western parts of the platform. Although evidences of dominating shallow-water depositional systems, spiculitic deposits have also been observed and reported from these provinces (Norsk Hydro A/S, 1984). Traditionally, spiculitic deposits have mostly been reported from, and associated with, deeper water depositional systems (Gates et al., 2004). However, shallow-water biosiliceous systems have in more recent years also been observed (Ehrenberg et al., 2001; Gammon, 2002; Gates et al., 2004). Beauchamp (1994) interpreted a shallow depositional setting for spiculites similar in composition and roughly age equivalent to the spiculitic deposits reported from the Finnmark Platform. In addition, a similar depositional setting has been reported from the Stappen High; the time equivalent formation, the Miseryfjellet Formation, also suggests shallow-water depositional environment on a newly submerged high (Worsley et al., 2001). Shallow-water indicators from the Late Permian succession on the western Finnmark Platform includes presence of cross-stratification and admixture of siliciclastic sand, as reported by the final well report of the western exploration well 7120/12-4 (Norsk Hydro A/S, 1984). Intercalations of siliciclastic material have also been observed from the seismic data in the area (Table 7).

In the Early Permian, the central platform areas were newly submerged- although still forming a positive structural high. Accordingly, the central platform reveals a similar depositional setting as reported from the Stappen High at the same time (Worsley et al., 2001). A major fault assigned to FF1 (Figures 12 and 13), separating the central and western provinces of the Finnmark Platform (Figures 12, 13, 43F and 43G), reveals Permian activity and is thought to be responsible for creation of significantly more accumulation space for the western platform areas.

Third-order relative sea level fluctuations have been reported from the Late Permian times (Ehrenberg et al., 2001; Gates et al., 2004). Consequently, the relative sea level likely rose and fell several times across the Finnmark Platform. Regional oceanographic changes and/or tectonic events might also have played a role in the relative sea level fluctuations (Ehrenberg et al., 2001). For the central and eastern Finnmark Platform, the relative sea level fluctuations seem to have played a critical role in developing the observed lithostratigraphic character. In contrast, the lithostratigraphic character of the eastern Finnmark Platform does not reveal the same significant influence. A possible explanation for this is that relative sea level fluctuations will have a greater impact on shallower depositional settings, as interpreted for the central and western platform, compared to deeper water settings, as interpreted for the eastern platform.


A)
Su1 - Early
Alluvial fan sediments
Land / denudation area
West
Central
East
N
50 km
B)
Su1 - Late
Shallow-shelf mixed siliciclastics and carbonates
Land / denudation area
Direction of clastic input
West
Central
East
N
50 km
C)
Su2 - Highstand
Inner-middle shelf warm water carbonates
Land
West
Central
East
N
50 km


D)
Su2 - Lowstand
Basinal evaporites
Exposed shelf carbonates
Land
West
Central
East
N
50 km
E)
Su3
Cool-water shelf carbonates
Land
Bryozoan buildup
West
Central
East
N
50 km
F)
Su4 - High relative sea level
Shallow-water shelf, spiculitic limestones
Cool-water temperate shelf, spiculitic limestones and chert
Land
Spiculitic limestone bank
Major fault
West
Central
East
N
50 km

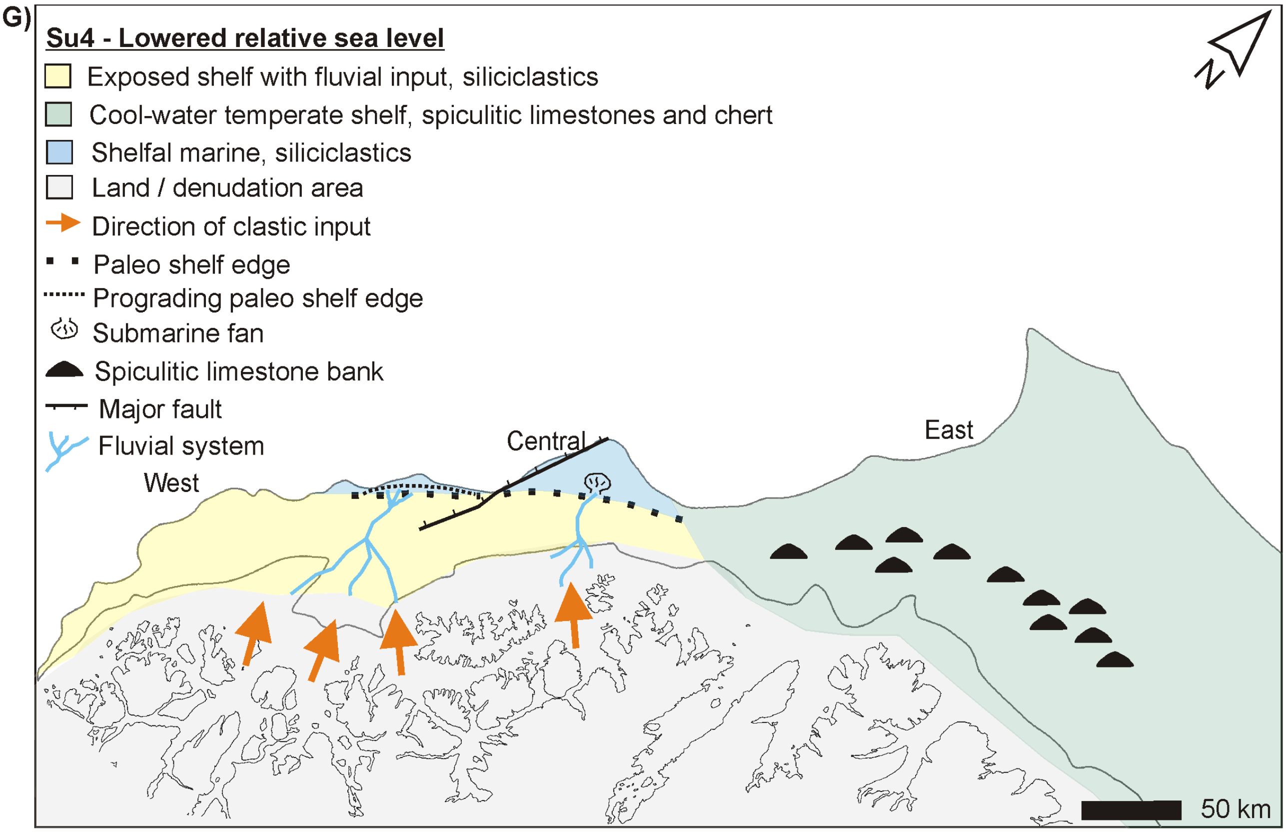


Figure 43: A-G) Proposed paleogeographic reconstruction of the Finnmark Platform during the Late Paleozoic times. See text for details for each of the evolutionary stages.

5.3 Relative sea level control on spiculitic limestone vs clastic deposition

Well and seismic data indicate competing clastic and carbonate environments on the central and western Finnmark Platform during Middle and Late Permian times (Table 7, Figures 7, 8, 40 and 42). These competing systems are thought to be closely linked to relative sea level fluctuations at the time.

5.3.1 Stage 1 – High relative sea level

During high relative sea level, the central and western platform likely represented shallow-water shelf systems with widespread deposition of spiculitic limestones (Figures 43F and 44i). Clastic systems might have existed further landward; however they were probably not powerful enough to shed debris into the submerged parts of the platform. The combination of shallow-water environment and absence of clastic input favors carbonate development.

5.3.2 Stage 2 – Drop in relative sea level

A following drop in relative sea level (Figure 44ii) is thought to result in subaerial exposure of the previously submerged platform areas (Figures 43G and 44ii). In addition, a lowered relative sea level is thought to facilitate deposition of clastic material from the hinterland, and the exposed platform, onto the platform (Figure 43G). Fluvial drainage systems likely transported and deposited terrigenous clastic sediments in addition to reworked spiculitic limestone deposits, across the platform areas (Figures 43G and 44ii). However, the siliciclastic input was probably higher onto the western part of the platform, as larger accumulation space was created by the hanging wall of the active major fault of FF1, which separates the west from the central platform (Figure 43G). Upon reaching the submerged outer platform areas (Figure 43G), the sediments formed a lense-shaped wedge (wedge 1 in Figure 44ii) as observed from the seismic data on the western platform (Figure 42).

5.3.3 Stage 3 – Rise in relative sea level

A renewed rise in relative sea level resulted in establishment of favorable conditions for carbonate development, resulting in deposition of a new spiculitic limestone unit (Figures 43F and 44iii). Similar depositional conditions as for stage 1 (Figure 44i) are thought to have dominated the platform areas (Figure 44iii).

5.3.4 Stage 4 – Drop in relative sea level

A subsequent drop in relative sea level terminated the favorable carbonate environment, and resulted in deposition of a new clastic layer across the platform (Figures 43G and 44iv). Seaward of the shelf break, a new lense-shaped wedge (wedge 2 in Figure 44iv) was deposited, onlapping the slope of the preceding wedge (wedge 1 in Figure 44iv). The result is lateral displacement of successively younger clastic wedges in a depositional downdip direction (Figures 42 and 44iv). A condensed section of spiculitic limestones is thought to be present in between the two wedges (Figure 44iv). Overall, the wedges reveal a down-stepping pattern (Figure 42) suggesting progressively lowered sea level towards the end of Permian. This coincides with a regional regression reported from the latest Permian times (Worsley et al., 2001). Based on this, the observed prograding lowstand wedges are thought to represent progradation of a paleo shelf edge (Figures 42 and 43G).

The central platform is thought to have remained a positive structural high throughout the Permian, and it might have experienced relative uplift compared to the western platform. The difference in available accommodation space is thought to be the reason for the observed significant difference in thickness of the Late Permian succession between the central and western platform areas (Figures 11, 40 and 42). On the central platform, prograding lowstand wedges have not been observed. This might be due to less clastic input onto this part of the platform. However, the seismic data revealed a fan-shaped geometry, possible representing a submarine fan (Figures 40). Contrasting the prograding clastic wedges, this feature was likely formed as a result of a single event. During a period of low relative sea level, fluvial systems might have transported alluvial fan sediments and eventually dumped them onto the central platform (Figure 43G).

5.4 Depositional analogue

Several of the stages of the Late Paleozoic depositional evolution of the Finnmark Platform appear similar to reported evolution from Bjørnøya located north of the study area (see Figure 3 for location). Figure 45A shows Worsley et al. (2001)'s interpreted outcrop section of Hambergfjellet, located on the southern part of Bjørnøya, while an idealized cross-section of the Finnmark Platform is proposed in Figure 45B. Throughout the Late Paleozoic times, the cliffs of Hambergfjellet reveal a similar behavior as observed for the central part of the Finnmark Platform. The SU1 and SU2 time-equivalents, Kapp Hanna Formation and Kapp Duner Formation respectively, reveal similar onlapping relationship onto a Late Paleozoic positive feature (Figure 45A), as has been observed for SU1 and SU2 on the central Finnmark Platform (Figure 45B). Upper Sakmarian-Lower Artinskian cold-water (lower SU3) sediments have been reported as being absent on Bjørnøya (Worsley et al., 2001), similar to what has been observed for the central and western Finnmark Platform. During the end of the Artinskian times, Hambergfjellet became submerged, resulting in deposition of the upper SU3 time-equivalent Hambergfjellet Formation (Figure 45A). At this time, the central and western Finnmark Platform still probably remained subaerially exposed, and consequently no sediments from the given time period have been observed in these areas (Figure 45B). The SU4 time-equivalent, the Miseryfjellet Formation, was deposited across Bjørnøya (Figure 45A) simultaneously as deposition of SU4 took place across the Finnmark Platform, including the newly submerged central and western parts of the platform (Figure 45B).

The overall similarities between the Late Paleozoic depositional regimes reported from Bjørnøya and what has been observed for the Finnmark Platform during this study, indicates that although complex Late Paleozoic development involving several phases of uplift, tilting, and faulting (Larssen et al., 2002), several locations in the southwestern Barents Sea seem to have experienced overall similar Late Paleozoic evolution.

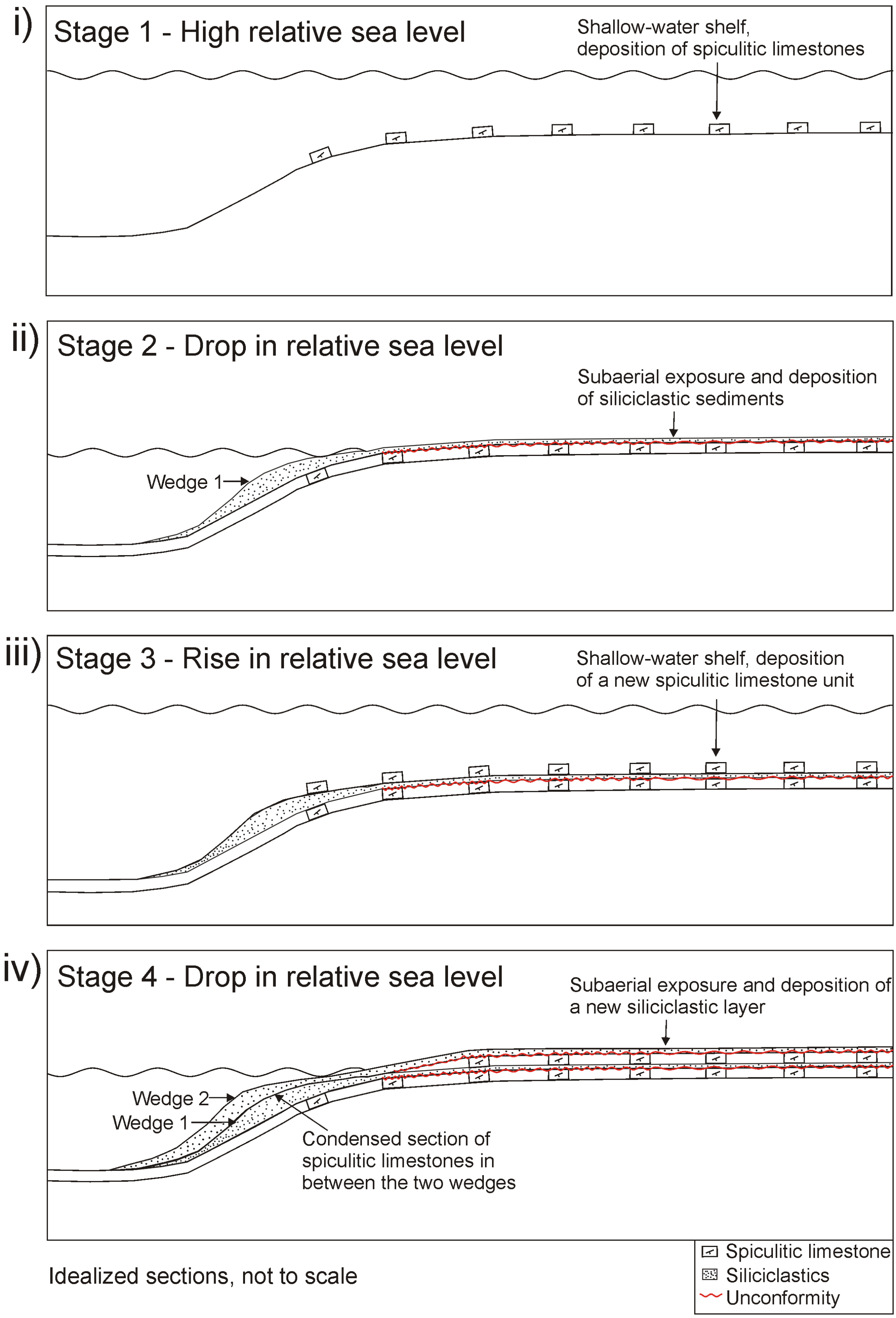


Figure 44: i – iv) Idealized sections showing the proposed relative sea level control on spiculitic limestone vs clastic deposition. During stages of high relative sea level (i and iii), a shallow-water shelf with extensive deposition of spiculitic limestones dominated. During stages of low relative sea level (ii and iv), the platform areas were subaerially exposed and deposition of siliciclastic sediments onto the platform occurred. Seaward of the shelf edge, prograding low-stand wedges developed. See text for more details.

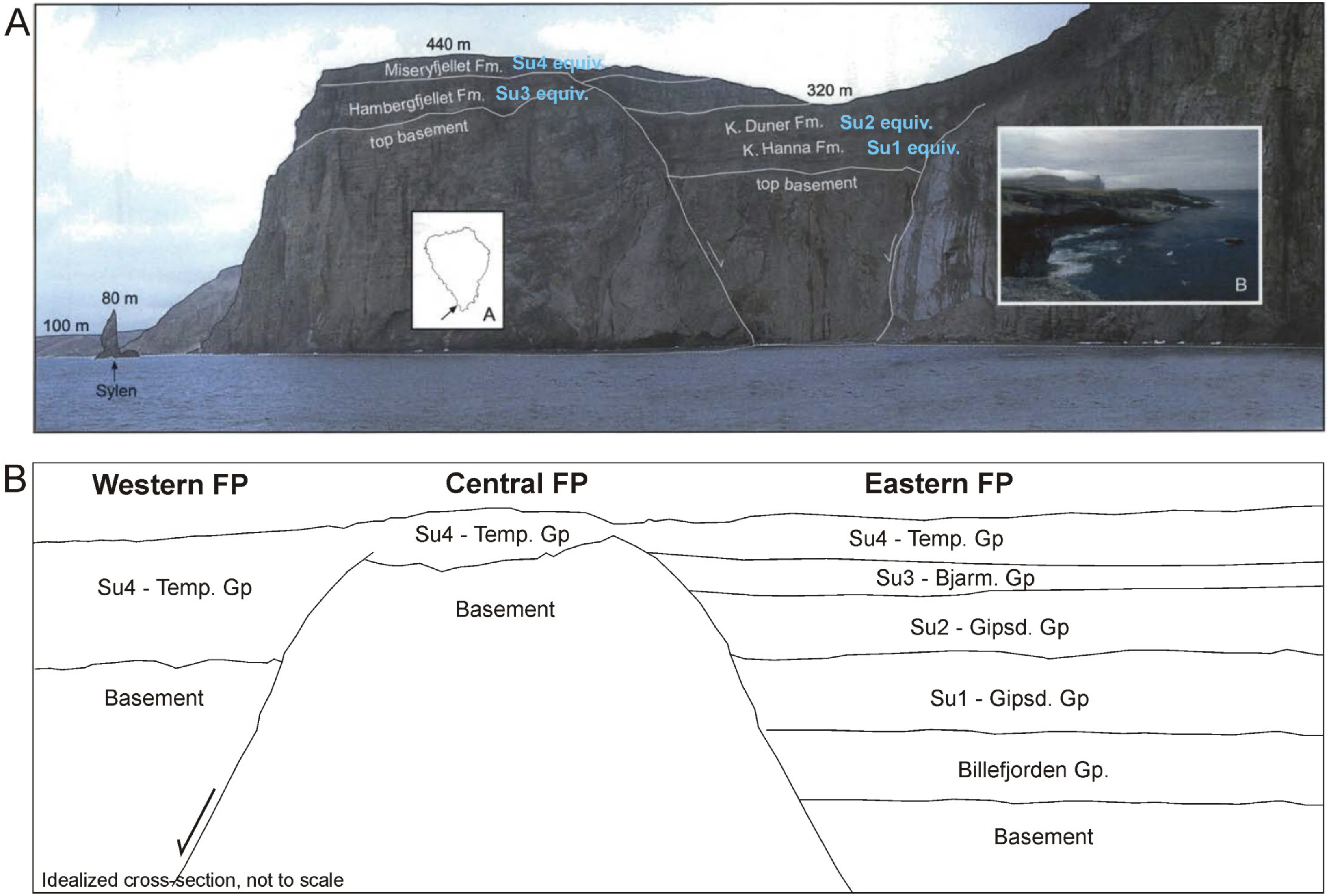


Figure 45: A) Worsley et al. (2001)'s interpreted outcrop section of Hambergfjellet, southern Bjørnøya. B) Idealized cross-section of the Finnmark Platform (FP). Note the similar onlapping relationships of the SU1- and SU2-equivalents onto the cliffs of Hambergfjellet (A) and the central Finnmark Platform (B).

Chapter 6: Conclusions

- Major differences, both structurally and stratigraphically, exist across the Finnmark Platform. Based on this, three provinces were defined:
  - Eastern province: Stable platform dominated by carbonate deposits
  - Central province: Fault-controlled structural high where carbonate-dominated units are observed to pinch-out
  - Western province: Structurally complex province dominated by clastic sediments
- Four fault families of initial normal fault origin have been identified. FF1, oriented NNE-SSW, suggests activity during the latest Permian times, whereas NE-SW oriented faults of FF2 seem to have been reactivated several times since its formation initiated in the Late Cretaceous times. A WNW-ESE striking fault assigned to FF3 is likely an offshore extension of the Trollfjord-Komagelv Fault Zone, which was active pre-deposition of the Upper Paleozoic succession on the Finnmark Platform. FF4 comprises NE-SW oriented basement-involved faults which are bounding tilted half-graben systems in the eastern province. These half-graben systems likely originate from a regional late Serpukhovian rifting event.
- Four seismic units largely corresponding to the well-known Late Paleozoic lithostratigraphic groups have been identified. SU1 correlates to the lower Gipsdalen Group and has been identified in all of the three provinces, although revealing different characteristics. SU2 correlates to the upper Gipsdalen Group and has been observed in the eastern, and partly, the central province. SU3 roughly correlates to the Bjarmeland Group unit and has mainly been observed in the eastern province. Lastly, SU4 correlates to the Tempelfjorden Group, which has been observed across the entire platform, although revealing contrasting characteristics.
- Overall, the Late Paleozoic evolution of the eastern Finnmark Platform resembles previous work done by e.g. Bugge et al. (1995) and Samuelsberg et al. (2003). Interpretation of regional 2D seismic data has resulted in an improved understanding of the Late Paleozoic development of the entire Finnmark Platform, which can be summarized as following:
  - The Finnmark Platform was site of localized fluvial sedimentation during the late Serpukhovian-Bashkirian (early SU1) times.
  - During the late Bashkirian-Kasimovian (late SU1) times, a marine incursion from the east flooded the platform, and a mixed siliciclastic and carbonate environment developed on the eastern platform. At the same time, the western and central

provinces represented a positive, subaerially exposed feature, obscuring the marine incursion from the east. Consequently, these areas were not site for deposition of the marine SU1 strata, which appears to pinch-out on the central platform areas.

- In the Gzhelian-Asselian (SU2) times, diachronous drowning of the siliciclastic provenance areas continued, resulting in development of a shallow warm-water carbonate shelf with scattered buildups on the eastern platform. The central and western provinces were still subaerially exposed, and the sediments of SU2 are observed to pinch-out on the central platform areas.
- An early Sakmarian (late SU2–early SU3) regional flooding event records a significant shift in the oceanographic circulation patterns. During the Sakmarian-Artinskian (SU3) times, a temperate cool-water platform with abundant bryozoan buildups dominating the platform margins, existed on the eastern Finnmark Platform. The central and western platform areas experienced marginal uplift and remained subaerially exposed. As a result of the uplift, the cold-water carbonates of SU3 did not reach as far westward on the platform as the underlying warm-water carbonates (SU2), although revealing a similar pinch-out near the central platform areas.
- Eventually, in the late Early Permian (SU4 times), the central and western provinces became submerged. Spiculites were deposited across the entire Finnmark Platform, although presumably under contrasting depositional settings. In the east, deeper and colder water deposition of spiculitic limestone and chert, with limestone bank development on the central platform areas, dominated. In the central and western provinces, a shallower-water setting with alternating deposition of spiculitic limestone and siliciclastics prevailed.

- On the central and western platform, relative sea level fluctuations seem to have played a critical role in developing the lithostratigraphic character of the Mid-Late Permian (SU4) succession. During highstands a shallow-water shelf with widespread spiculitic limestone deposition dominated. During lowstands, large parts of the platform areas were exposed, and fluvial drainage systems transported clastic sediments onto the platform.
- Overall, the proposed depositional evolution of the Finnmark Platform appears highly similar to Worsley et al. (2001)'s reported evolution of Bjørnøya, where similar onlapping relationships onto a Late Paleozoic positive feature have been described. This might indicate that although complex Late Paleozoic development involving several stages of uplift, faulting and tilting, overall similar depositional settings existed on Bjørnøya and the Finnmark Platform during the Late Paleozoic times.

Chapter 7: References

Ahmed, W., 2012, Structural Analysis of the Troms-Finnmark Fault Complex, SW Barents Sea, University of Oslo, Oslo, 133 p.

Beauchamp, B., 1994, Permian climatic cooling in the Canadian Arctic: Geological Society of America Special Papers, v. 288, p. 229-246.

Beauchamp, B., and A. Baud, 2002, Growth and demise of Permian biogenic chert along northwest Pangea: evidence for end-Permian collapse of thermohaline circulation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 184, p. 37-63.

Beauchamp, B., and A. Desrochers, 1997, Permian warm-to very cold-water carbonates and cherts in northwest Pangea: James, N.P., Clarke, J. (Eds.), Cool Water Carbonates, Society of Sedimentary Geology (SEPM), v. 56, p. 327-347.

Blendinger, W., B. Bowlin, F. Zijp, G. Darke, and M. Ekroll, 1997, Carbonate buildup flank deposits: an example from the Permian (Barents Sea, northern Norway) challenges classical facies models: Sedimentary Geology, v. 112, p. 89-103.

Bugge, T., G. Mangerud, G. Elvebakk, A. Mørk, I. Nilsson, S. Fanavoll, and J. O. Vigran, 1995, The Upper Palaeozoic succession on the Finnmark Platform, Barents Sea: Norsk Geologisk Tidsskrift, v. 75, p. 3-30.

Colpaert, A., N. Pickard, J. Mienert, L. B. Henriksen, B. Rafaelsen, and K. Andreassen, 2007, 3D seismic analysis of an Upper Palaeozoic carbonate succession of the Eastern Finnmark Platform area, Norwegian Barents Sea: Sedimentary Geology, v. 197, p. 79-98.

Ehrenberg, S., 2004, Factors controlling porosity in Upper Carboniferous–Lower Permian carbonate strata of the Barents Sea: AAPG bulletin, v. 88, p. 1653-1676.

Ehrenberg, S., N. Pickard, L. Henriksen, T. Svana, P. Gutteridge, and D. Macdonald, 2001, A depositional and sequence stratigraphic model for cold-water, spiculitic strata based on the Kapp Starostin Formation (Permian) of Spitsbergen and equivalent deposits from the Barents Sea: AAPG bulletin, v. 85, p. 2061-2088.

Ehrenberg, S. N., E. B. Nielsen, T. A. Svånå, and L. Stemmerik, 1998, Depositional evolution of the Finnmark carbonate platform, Barents Sea: results from wells 7128/6-1 and 7128/4-1: Norsk Geologisk Tidsskrift, v. 78, p. 185-224.

Ehrenberg, S. N., N. A. H. Pickard, T. A. Svånå, I. Nilsson, and V. I. Davydov, 2000, Sequence stratigraphy of the inner Finnmark carbonate platform (Upper Carboniferous-Permian), Barents Sea-correlation between well 7128/6-1 and the shallow IKU cores: Norsk Geologisk Tidsskrift, v. 80, p. 129-161.

Elvebakk, G., D. W. Hunt, and L. Stemmerik, 2002, From isolated buildups to buildup mosaics: 3D seismic sheds new light on upper Carboniferous-Permian fault controlled carbonate buildups, Norwegian Barents Sea: Sedimentary Geology, v. 152, p. 7-17.

Faleide, J. I., F. Tsikalas, A. J. Breivik, R. Mjelde, O. Ritzmann, Ø. Engen, J. Wilson, and O. Eldholm, 2008, Structure and evolution of the continental margin off Norway and the Barents Sea: Episodes, v. 31, p. 82-91.

Gabrielsen, R., 1984, Long-lived fault zones and their influence on the tectonic development of the southwestern Barents Sea: Journal of the Geological Society, v. 141, p. 651-662.

Gabrielsen, R. H., R. B. Færseth, L. N. Jensen, J. E. Kalheim, and F. Riis, 1990, Structural Elements of the Norwegian Continental Shelf. Pt. 1. The Barents Sea Region: Norwegian Petroleum Directorate Bulletin, v. 6, p. 1-47.

Gammon, P. R., 2002, Shallow shelf biosiliceous sedimentation: a terrestrial aridity record: Abstracts-Geological Society of America, p. 553.

Gates, L. M., N. P. James, and B. Beauchamp, 2004, A glass ramp: shallow-water Permian spiculitic chert sedimentation, Sverdrup Basin, Arctic Canada: Sedimentary Geology, v. 168, p. 125-147.

Gernigon, L., M. Brönner, D. Roberts, O. Olesen, A. Nasuti, and T. Yamasaki, 2014, Crustal and basin evolution of the southwestern Barents Sea: From Caledonian orogeny to continental breakup: Tectonics, v. 33, p. 347-373.

Gjelberg, J., and R. Steel, 1983, Middle Carboniferous marine transgression, Bjørnøya, Svalbard: facies sequences from an interplay of sea level changes and tectonics: Geological Journal, v. 18, p. 1-19.

Golonka, J., N. Y. Bocharova, D. Ford, M. E. Edrich, J. Bednarczyk, and J. Wildharber, 2003, Paleogeographic reconstructions and basins development of the Arctic: Marine and Petroleum Geology, v. 20, p. 211-248.

Gudlaugsson, S. T., J. I. Faleide, S. E. Johansen, and A. J. Breivik, 1998, Late Palaeozoic structural development of the South-western Barents Sea: Marine and Petroleum Geology, v. 15, p. 73-102.

Halland, E. K., A. Bjørnestad, I. T. Gjeldvik, M. Bjørheim, C. Magnus, I. M. Meling, J. Mujezinovic, F. Riis, R. S. Rød, V. T. H. Pham, and I. Tappel, 2014, The Barents Sea, CO2 Storage Atlas Barents Sea, Norwegian Petroleum Directorate p. 108-145.

Henriksen, E., A. Ryseth, G. Larssen, T. Heide, K. Rønning, K. Sollid, and A. Stoupakova, 2011, Tectonostratigraphy of the greater Barents Sea: implications for petroleum systems: Geological Society, London, Memoirs, v. 35, p. 163-195.

Johannessen, E., and R. Steel, 1992, Mid-Carboniferous extension and rift-infill sequences in the Billefjorden Trough, Svalbard: Norsk geologisk tidsskrift, v. 72, p. 35-48.

Kjøde, J., K. Storetvedt, D. Roberts, and A. Gidskehaug, 1978, Palaeomagnetic evidence for large-scale dextral movement along the Trollfjord-Komagelv Fault, Finnmark, north Norway: Physics of the Earth and Planetary Interiors, v. 16, p. 132-144.

Larssen, G., G. Elvebakk, L. B. Henriksen, S. Kristensen, I. Nilsson, T. Samuelsberg, T. Svånå, L. Stemmerik, and D. Worsley, 2002, Upper Palaeozoic lithostratigraphy of the Southern Norwegian Barents Sea: Norwegian Petroleum Directorate Bulletin, v. 9, 76 p.

Lawver, L. A., L. M. Gahagan, and I. Norton, 2011, Palaeogeographic and tectonic evolution of the Arctic region during the Palaeozoic: Geological Society, London, Memoirs, v. 35, p. 61-77.

Mosar, J., T. H. Torsvik, and t. B. Team, 2002, Opening the Norwegian and Greenland Seas: Plate tectonics in Mid Norway since the Late Permian, BATLAS - Mid Norway plate reconstruction atlas with global and Atlantic perspectives: Trondheim, Geological Survey of Norway, p. 48-59.

Norsk Hydro A/S, 1984, Final report well 7120/12-4, NPD factpages: (accessed May 12, 2015), http://www.npd.no/engelsk/cwi/pbl/wellbore_documents/99_01_Completion_Report.pdf, p. 1-111.

Rafaelsen, B., G. Elvebakk, K. Andreassen, L. Stemmerik, A. Colpaert, and T. J. Samuelsberg, 2008, From detached to attached carbonate buildup complexes - 3D seismic data from the upper Palaeozoic, Finnmark Platform, southwestern Barents Sea: Sedimentary Geology, v. 206, p. 17-32.

Rice, A., R. Gayer, D. Robinson, and R. Bevins, 1989, Strike-slip restoration of the Barents Sea Caledonides Terrane, Finnmark, north Norway: Tectonics, v. 8, p. 247-264.

Roberts, D., and A. Siedlecka, 2002, Timanian orogenic deformation along the northeastern margin of Baltica, Northwest Russia and Northeast Norway, and Avalonian–Cadomian connections: Tectonophysics, v. 352, p. 169-184.

Samuelsberg, T. J., G. Elvebakk, and L. Stemmerik, 2003, Late Palaeozoic evolution of the Finnmark Platform, southern Norwegian Barents Sea: Norsk Geologisk Tidsskrift, v. 83, p. 351-362.

Steel, R. J., and D. Worsley, 1984, Svalbard's post-Caledonian strata—an atlas of sedimentational patterns and palaeogeographic evolution, Petroleum geology of the North European margin, Springer, p. 109-135.
Stemmerik, L., 1997, Permian (Artinskian Kazanian) Cool-Water Carbonates in North Greenland, Svalbard and the Western Barents Sea: James, N.P., Clarke, J. (Eds.), Cool Water Carbonates, Society of Sedimentary Geology (SEPM), v.56, p.349-364.
Stemmerik, L., 2000, Late Palaeozoic evolution of the North Atlantic margin of Pangea: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 161, p. 95-126.
Stemmerik, L., G. Elvebakk, and D. Worsley, 1999, Upper Palaeozoic carbonate reservoirs on the Norwegian Arctic Shelf: Delineation of reservoir models with application to the Loppa High: Petroleum Geoscience, v. 5, p. 173-187.
Stemmerik, L., and D. Worsley, 2005, 30 years on - Arctic Upper Palaeozoic stratigraphy, depositional evolution and hydrocarbon prospectivity: Norsk Geologisk Tidsskrift, v. 85, p. 151-168.
Torsvik, T. H., D. Carlos, J. Mosar, L. R. M. Cocks, and T. N. Malme, 2002, Global reconstructions and North Atlantic paleogeography 440 Ma to Recent, BATLAS - Mid Norway plate reconstruction atlas with global and Atlantic perspectives, Geological Survey of Norway, p. 18-39.
Worsley, D., 2008, The post-Caledonian development of Svalbard and the western Barents Sea: Polar Research, v. 27, p. 298-317.
Worsley, D., T. Agdestein, J. G. Gjelberg, K. Kirkemo, A. Mørk, I. Nilsson, S. Olaussen, R. J. Steel, and L. Stemmerik, 2001, The geological evolution of Bjørnøya, Arctic Norway: implications for the Barents Shelf: Norwegian Journal of Geology, v. 81, p. 195-234.
Ziegler, P. A., 1989, Evolution of the North Atlantic—an overview, Extensional Tectonics and Stratigraphy of the North Atlantic Margins, American Association of Petroleum Geologists Memoir, v. 46, p. 111-129.