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Structural evolution and fluvio-deltaic sedimentary architecture in salt-influenced rift-basins - examples from the Snadd Formation in the Nordkapp and Tiddlybanken basins

by

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MSc Thesis

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Abstract

The Nordkapp and Tiddlybanken basins are examples of salt sedimentary basins with thick successions of Triassic-Middle Jurassic fluvio-deltaic basin infill in the Barents Sea. The Middle to Upper Triassic Snadd Formation represent two regressive-transgressive fluvio-deltaic mega-sequences systems extending across the entire Barents Sea. These large fluvio-deltaic systems were generated as a result of the exposure of the Ural Mountains and Fennoscandia.

The Nordkapp and Tiddlybanken basins formed during Devonian to Carboniferous, with salt deposited in a shallow evaporitic basin during the Late Carboniferous and Early Permian under the influence of regional extension. Salt growth was initiated in Early-Middle Triassic in the Nordkapp Basin and Middle Triassic in the Tiddlybanken Basin. Several salt mini-basins were formed due to diachronous salt growth in response to differential loading in the Early to Middle Triassic, because of the initial progradation of fluvio-deltaic systems. The fluvial stratigraphic architecture and style in the mini-basins is controlled by the interplay between subsidence rate (and subsequent accommodation creation) and sediment delivery rate.

The regressive and transgressive mega-sequences represent two forestepping to backstepping fluvio-deltaic clastic wedges in the Snadd Formation. Depositional environments range from upper delta plain to marine environments, but are mostly occupied by flood- and delta plain environments with various types of fluvial channel systems.

The salt diapirism interaction with the fluvio-deltaic systems has generated rim-synclines along the salt walls with large fluvial systems captured by the rim-synclines, resulting in fill-spill infill pattern of the salt mini-basins. In the lower progradational and retrogradational units the dominant fluvial character is meandering to anastomosing, with underfilled conditions in the salt mini-basins. The middle part is a succession with balanced to overfilled basin conditions with vertically stacked channel fills with broad meandering to braided systems/channel complexes. The upper part is dominantly balanced to underfilled, with meandering and anastomosing fluvial styles. A lacustrine environment is also identified within this package. With a greater net-to-gross and channel proportion in the middle part, this is expected to have a good to excellent reservoir quality potential. The dominantly fine-grained under and overlaying parts, seal potential stratigraphic traps such as fluvial channels in the mini-basin and/or updip along a structure. Organic-rich deposits are expected within the lacustrine environment, which have the opportunity to act as a potential source rock for the embedded channels or overlaying Jurassic strata.

Acknowledgements

After a long and arduous journey, my project is coming to an end. It has been difficult, but also a tremendous learning experience and fun. I would like to take this opportunity to reflect on the many people who have helped me along the way.

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1.0 Introduction

Salt-related sedimentary basins around the world have successful hydrocarbon exploration histories. Timing of the salt movement influences the sedimentation patterns and creates localized subsidence that affects the source, reservoir, trap and seal rocks, and therefore the prospectivity of salt influenced basins (Archer et al., 2012). Fluvial interaction with salt growth in supra-salt minibasins is the focus of the thesis and documented in the several basins (e.g. Triassic Moenkopi Formation in the Paradox Basin; Triassic Skagerrak Formation of Central North Sea; Carroza Formation in the La Popa Basin; and Pre-Caspian Basin) (Banham and Mountey, 2013b). The fluvial styles and successions are described in the analogue salt-walled mini-basins (Banham and Mountney, 2013a, 2013b) and show great potential for good reservoir quality in provinces with salt tectonics and fluvio-deltaic environments (Banham and Mountney, 2013b).

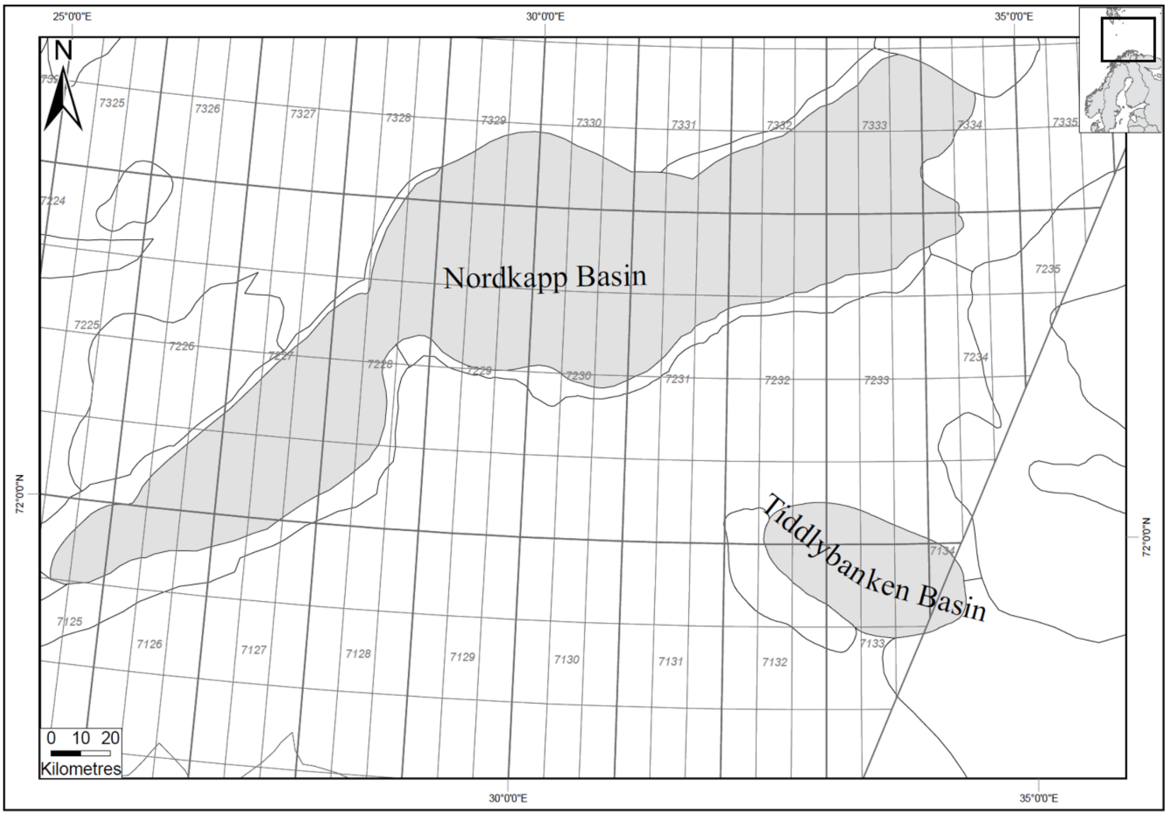


Figure 1: Location of the Nordkapp and Tiddlybanken basins in the Barents Sea.

General studies have been conducted to determine how different sedimentary environments are influenced by halokinesis movement and the subsequent high rates of basin floor subsidence (Banham and Mountney, 2013a; 2013b). This thesis is driven by the purpose of identifying basins/mini-basins in the Triassic Snadd to understand the tectonostratigraphic evolution, that can result in improved identification of source and reservoir rocks in the basins. It involves assessing the structural evolution, controlling factors of fluvio-deltaic sedimentation and stratigraphic and structural architecture of mini-basins influenced by salt tectonics. The Triassic Tiddlybanken and Nordkapp basins are characterized by its fluvio-deltaic systems with salt-wall interaction and by their salt diapirs (Bugge et al., 2002), that resulted in thick packages of Triassic strata within these basins (Figure 1). These sedimentary basins are located in the SW Barents Sea region and are chosen as examples to illustrate the interaction between salt diapirism and sediment supply. This study will test and challenge previous studies' conceptual models and theories, and analyze the role of the different variables in the specific Nordkapp and Tiddlybanken basins that can be of great interest for their hydrocarbon potential.

1.1 Aim of study

The aim of this study is to distinguish the Triassic sequences in the selected basins, or local mini-basins, through Triassic times in order to understand the controlling factors, analyzing stacking patterns, seismic facies, and adjacent well data. The emphasis of the study is to improve our ability to predict areas of interest by identifying potential candidates of source and reservoir rocks in the rim-synclines. The channel systems of the Snadd Formation have been selected to demonstrate examples of fluvio-deltaic systems in the Nordkapp and Tiddlybanken Basin.

1.2 Objectives

The main objective of the thesis is to investigate the structural evolution and the fluvio-deltaic architecture of Triassic units in the Nordkapp and Tiddlybanken salt-walled basins. This is subdivided into the following sub-objectives, which are to:

- identify infill patterns from seismic facies, amplitude extractions, well data and analogue data;
- investigate the evolution of accommodation creation to identify fluvial styles;
- study and determine characterization of fluvial reservoir types, architectures and properties;
- investigate spatial and temporal style/variability of fluvial infill patterns; and
- identify potential for stratigraphic trapping in salt-walled basins/mini-basins in fluvial successions.

2.0 Geological framework

2.1 Regional geology

2.1.1 The Greater Barents Sea

The Barents Sea region is bounded by the Norwegian and Russian coasts to the south, Franz Josef Land and Svalbard archipelagos to the north and the deeper waters of the Norwegian Sea to the west (Dore, 1995; Henriksen et al., 2011).

According to Henriksen et al. (2011) the greater Barents Sea has experienced three main tectonic phases from Late Paleozoic to Paleogene. Firstly, the western areas experienced uplift in Paleozoic due to the Caledonian Orogeny, which led to sediment distribution towards the carbonate platforms in the east. Secondly, the clastic sediment distribution pattern shifted and became more widespread as the Uralide Orogeny induced uplift in the east. Lastly, the present day basin configuration is caused by major Late Mesozoic-Cenozoic rifting in the Western Barents Sea (Henriksen et al., 2011).

The first phase is dominated by the Iapetus Ocean closing and leading to the separation of the Eurasian and Laurentian plates, as a result of the Caledonian Orogeny in the west. In the Ordovician times deformation began, and it culminated in Silurian times (Gee et al., 2008; Henriksen et al., 2011).

During the second phase, crustal extension took place in Late Paleozoic, forming half grabens and eventually leading to the creation of a regional sag basin that cover major parts of the Barents Sea (Henriksen et al., 2011). After the Caledonian Orogeny, the Barents Sea experienced uplift in the east as an implication of the creation of the Uralide Orogeny, during Devonian and Carboniferous - Permian plate collision (Henriksen et al., 2011; O´Leary et al., 2004). The event contributed to a physiographic change in the basins in Late Paleozoic to Triassic. The Nordkapp Basin shows indications of local post-Permian subsidence and depocenters (Henriksen et al., 2011). The tectonic regime of Devonian comprised of crustal extension and compression (Bjørlykke, 2010). The rifting continued into Carboniferous in the Barents Sea and Svalbard, due to the initiation of divergence between the active tectonic plates in the Atlantic rift system (between Norway and Greenland) (Henriksen et al., 2011). Bjørlykke (2010) states that during the Carboniferous rifting phase, interconnected extensional/rift basins were formed and separated by fault-bounded highs and the basins were filled with syn-rift deposits. This led to the creation of the Nordkapp Basin in Devonian to Carboniferous time. By

Late Carboniferous to Early Permian, the continent collision between Baltica and West Siberian Craton had reached the eastern Barents Sea (Henriksen et al., 2011; Smelror et al., 2009). Shallow marine carbonates dominate the Barents Sea in Early Carboniferous and Permian with vast amounts of salt deposited in the Nordkapp and Tiddlybanken basins (Lundschien et al., 2014). In the eastern areas, in Middle Carboniferous Baltica and West Sibirian Cration plates collided, creating the Ural Mountains (Ryseth, 2014; Smelror et al., 2009)

In the third phase, the Mesozoic extensional events were dominant towards the western Atlantic rift system (Henriksen et al., 2011). In (Permo-)Triassic times a rapid foreland basin was generated on the eastern margin of the Timian-Pechora basin, associated with the Uralian Orogeny (O'Leary et al., 2004). In Early Triassic the Barents Sea, large amounts of siliciclastic sediments were transported from the Ural Mountains and Baltic Shield, and deposited (Bjørlykke, 2010). The rifting between Norway and Greenland in the North Atlantic rifting system ceased in Middle Triassic (Glørstad-Clark et al., 2010). Infilling of the Barents Sea through Middle to Late Triassic times (Snadd Formation) was a part of the Mesozoic infilling, that is characterized as a southwestward prograding siliciclastic wedge (Klausen et al., 2015). In Late Jurassic to Early Cretaceous the tectonic activity was great, and it formed the present day configuration of the basins and highs. The active tectonics culminated and major subsidence occurred in Early Cretaceous in the western areas of the Barents Sea (Gabrielsen et al., 1990; Henriksen et al., 2011). The many Late Mesozoic and Early Cenozoic rifting phases formed deep basins and highs in the SW Barents Sea (Bjørlykke, 2010). This time was dominated by the rifting and opening of the Arctic Basin with an associated seafloor spreading (Henriksen et al., 2011; Worsley, 2008).

The fourth phase of importance is the Cenozoic evolution of the Barents Sea closely tied to the opening of the Norwegian-Greenland Sea. Indications of compressional features and possible phases of compression are identified in Oligocene to Miocene structures, as a result of the plate tectonic changes in the NE Atlantic, in addition to major Alpine deformation phases. Compressional and inversion structures from this time are widespread throughout the Barents Sea (Dore and Lundin, 1996; Henriksen et al., 2011). During Cenozoic, periods of uplift and erosion has led to limited preservation of Cenozoic sediments and older strata, in particular in the western and northwestern parts of the Barents Sea. An estimate of erosion is approximately 1000-1500 m in the SW Barents Sea. The evolution of Late Cenozoic is dominated by subsidence and burial of eroded sediments from the uplifted highs (Bjørlykke, 2010).

2.2 Evolution and infill-story of the Nordkapp and Tiddlybanken basins

The Nordkapp Basin is characterized by salt diapirs of Paleozoic age (Henriksen et al., 2011) (Figure 2). Gabrielsen et al. (1990) states that the Tiddlybanken Basin has similarities with the Nordkapp Basin, however the development of the Tiddlybanken basin is not well established.

According to Nilsen et al. (1995) the major tectonic events in the Barents Sea have controlled the initiation, growth and reactivation of the salt diapirs in the Nordkapp Basin. The Nordkapp Basin appeared as a rift basin in the Devonian to Carboniferous times, with salt deposited in a shallow evaporitic basin during the Late Carboniferous and Early Permian, under the influence of regional extension (Bjørlykke, 2010; Ramberg et al., 2008). Shallow carbonates were dominating the Barents Sea in the Late Carboniferous and Permian. Like the Nordkapp Basin, large quantities of salt were deposited in the Tiddlybanken Basin during this time (Lundschien et al., 2014). Halokinesis in the Nordkapp Basin was initiated in the Early Triassic during regional extension. It experienced diapiric growth from Middle to Late Triassic while gravity gliding-induced-diapiric reactivation occurred in the Late Cretaceous. Salt growth initiation in the Tiddlybanken Basin occurs in Middle Triassic (Lundschien et al., 2014). Regional contraction in Eocene to Oligocene triggered the last phase of movement of the salt structures in the Nordkapp Basin (Nilsen et al., 1995). There was uplift of the Kola Monocline in addition to inversion on the Fedynsky High, in Cretaceous to Cenozoic times (Stroupakova et al., 2011). It is expected that these events affected that the adjacent Tiddlybanken Basin.

In contradiction to Nilsen et al. (1995) who argues that the salt movement is a result of regional tectonics, other authors believe that differential loading of sediments initiated the salt diapirism, creating nearly vertical salt diapirs that reached or almost reached the delta plain (Norwegian Petroleum Directorate, 2013; Bjørlykke, 2010).

2.2.1 The Triassic basin infill and climate

The present day Hammerfest-, Tromsø-, Bjørnøy- and Nordkapp basins have experienced significant subsidence and high sediment supply through Triassic, filling the basins. The salt reached the seafloor, making the seafloor bulge upwards. Eventually some salt walls pierced through the seafloor, creating ridges as topographic highs, which controlled the sediment deposition and patterns in the basins in Triassic (Ramberg et al., 2008) (Figure 2).

Deposition in Early to Middle Triassic is largely influenced by the topography and paleo-highs present in the basins (Glørstad-Clark et al., 2010). The architecture and provenance studies of the clinoforms in the Early to Middle Triassic sequences suggest derivations from the Baltic Shield in the south and the Uralian Mountains in the southeast and east. It is dominated by progradational and retrogradational patterns that vary with the repositioning of the shoreline due to changes in relative sea level (Glørstad-Clark et al., 2011). During the Triassic there was gradual sedimentary infill of the basins in the Barents Sea (Glørstad-Clark et al., 2010) and as the continental regime prevailed, the prograding deltaic systems continued to infill the regional basin (Bjørlykke, 2010) (Figure 3). The Triassic sediments are dominantly shales and sandstones, where there seems to be a coarsening upwards trend in the clastic rocks, in the younger sequences of the period (Bjørlykke, 2010).

Nordkapp Basin shifted between being a shallow sea to continental conditions (dry land) with vast alluvial plains throughout Triassic. In Middle Triassic, the basin was a marine embayment with deposition of organic-rich mudstones (considered source rocks). During Late Triassic, large deltaic and fluvial systems transported huge volumes of sand. These were deposited on the coastal and alluvial plains in the Nordkapp Basin, and make up some of the best quality reservoir rocks present in the Barents Sea (Ramberg et al., 2008).

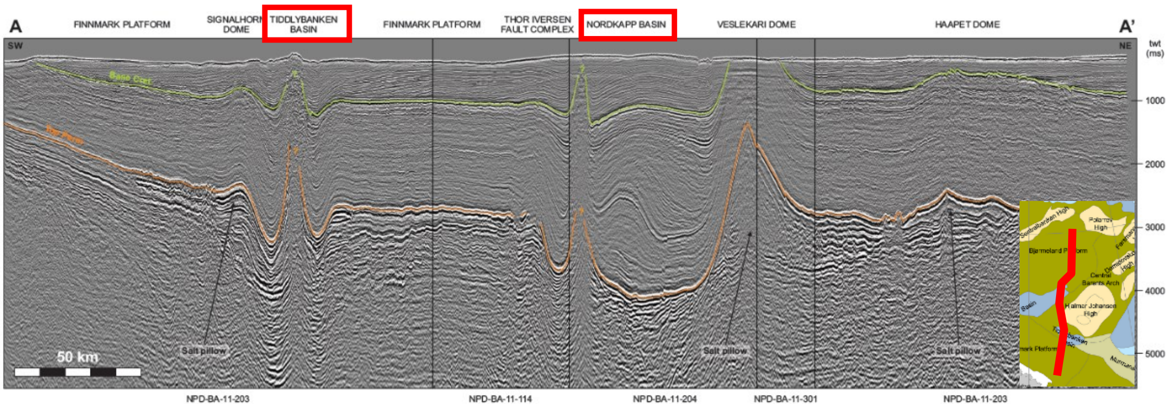


Figure 2: Regional intersection in a north-south direction with the Tiddlybanken and Nordkapp basins (modified after Mattingsdal et a.l, 2015).

Climate variations through Triassic

Spore-pollen is used to evaluate the paleoclimatic fluctuations in Triassic in the Barents Sea by Hochuli and Vigran (2010). Through the palynoclimatolgy documentation it is clear that the Triassic was a period of extreme "hot-house". Ice free polar areas and flora associated with warm temperatures are recorded in Middle to late Triassic. However, Middle to Late Carnian strata is considered to be dryer (Hochuli and Vigran, 2010). The records show that there was a rapid change from dry to humid climate conditions from Early Carnian through Late Carnian. Late Carnian to Early Norian has both of a warm and humid climate with presence of floodplain deposits and coal-bearing sediments (Ryseth, 2014). The climate in Nordkapp Basin during Late Triassic, based on palynological data, is indicating that the post-Early Carnian period existed during a very warm climate (Hochuli and Vigran, 2010; Ryseth, 2014). The Early Jurassic is considered to have more humid conditions compared to Late Triassic (Ryseth, 2014).

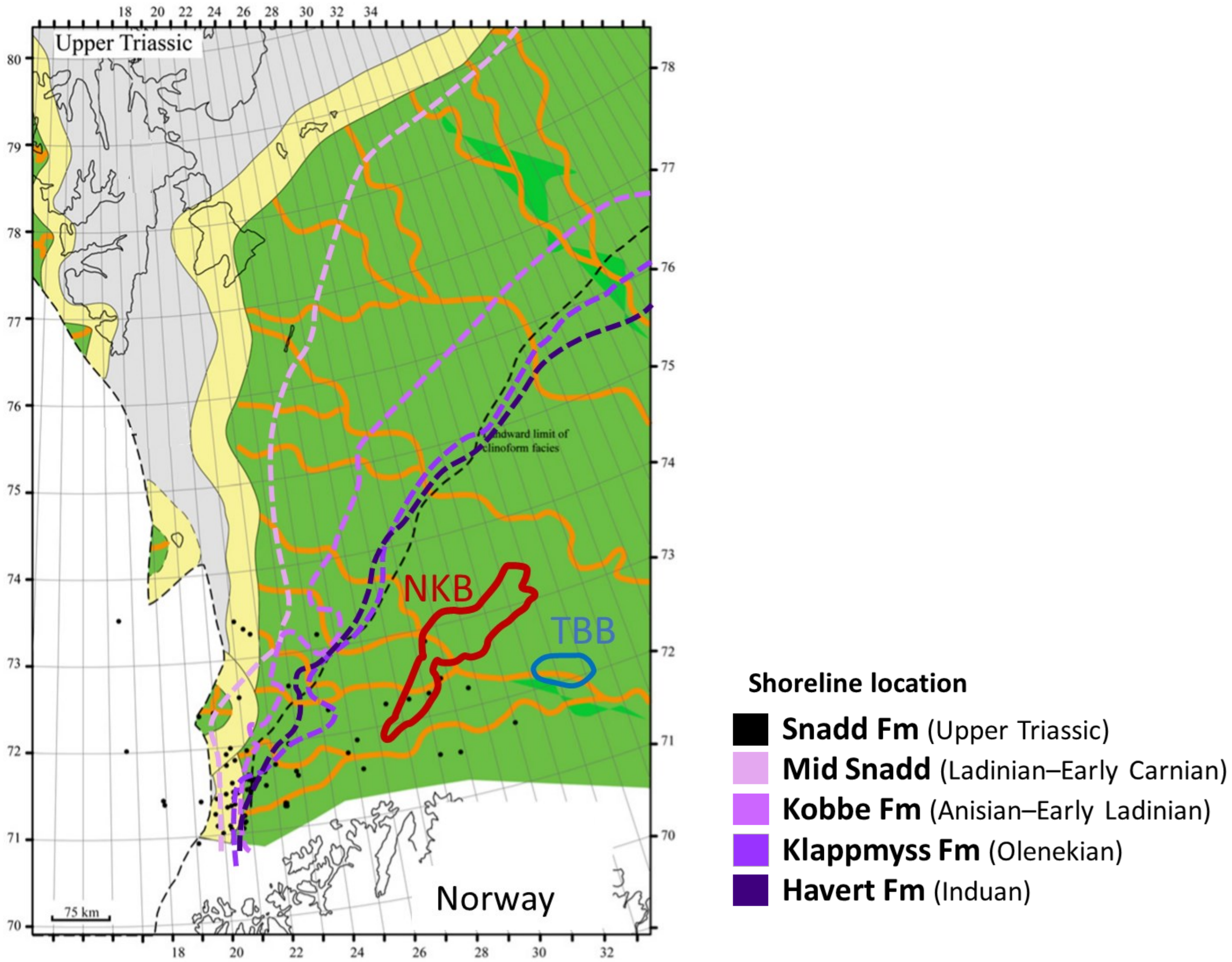


Figure 3: Paleogeographic reconstruction of maximum progradation of the second-order sequences of the Triassic based on the interpretation of Glørstad-Clark et al. (2010) (modified after Glørstad-Clark et al., (2010)).

3.0 Dataset and methodology

3.1 Dataset

The study area is covered by several 3D and 2D seismic surveys and well data. The dataset utilized includes selected 2D and 3D surveys over the Tiddlybanken basin, the Nordkapp Basin and the NE Finnmark Platform in the eastern Norwegian Barents Sea (Figure 4). The 3D and 2D seismic data has been provided by A/S Norske Shell.

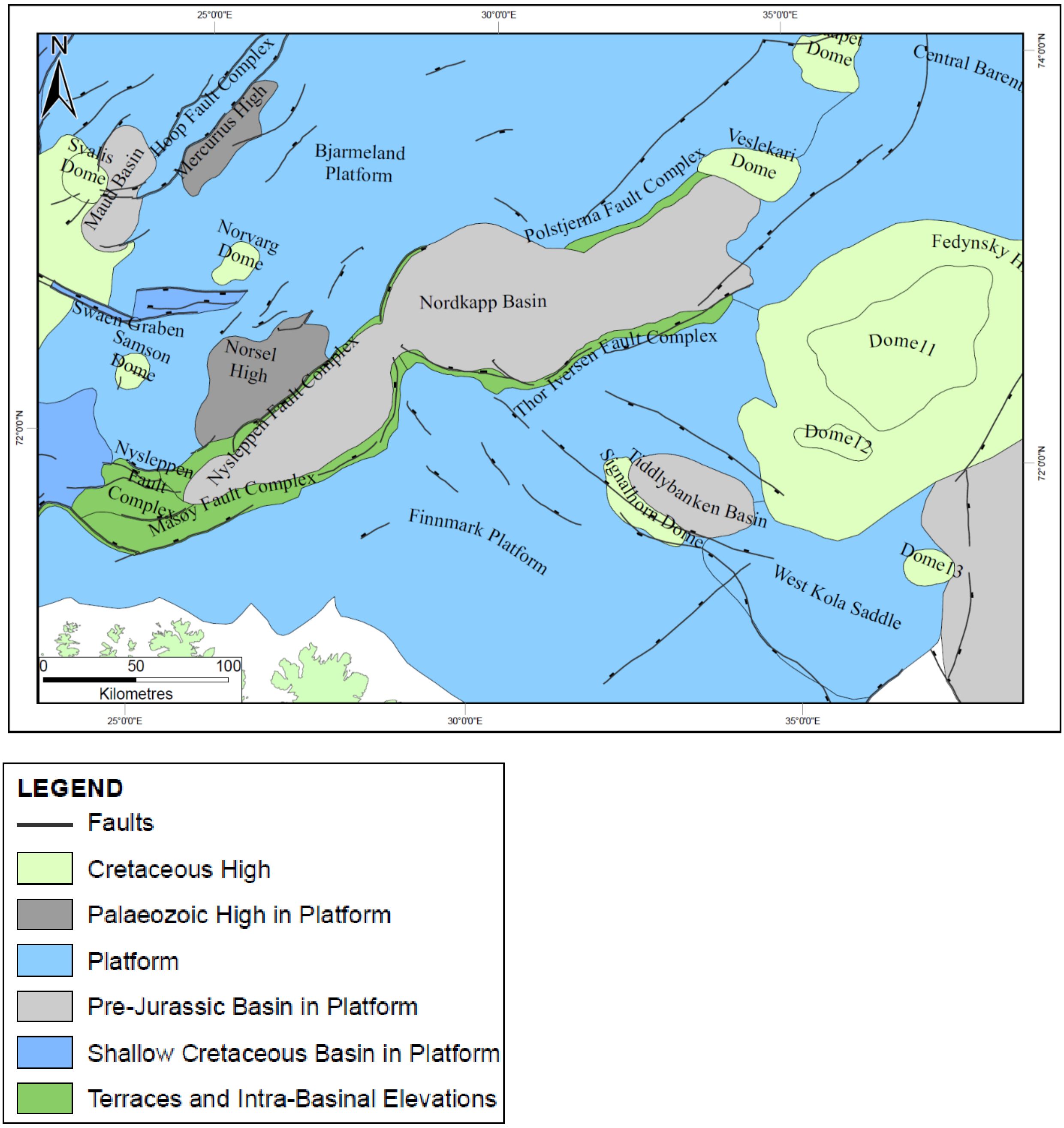


Figure 4: Map over the study areas, the Tiddlybanken and Nordkapp basins, and surrounding structural elements.

3.1.1 Seismic data

The seismic data includes three key 3D seismic surveys and five 2D seismic surveys (Figure 5). The 3D seismic data used for the project is located in the Tiddlybanken Basin, NE Finnmark Platform and NE Nordkapp Basin. The seismic surveys have been selected to illustrate fluvial styles in the different basinal structure settings, such as stable platform areas (survey ST9802), proximal salt basin with salt withdrawl synclines (survey ST14004) and basinal margin of a salt basin (survey BG0804) (Table 1). The 2D seismic data allow for correlation between 3D surveys and provides placement of 3D data within a regional context (Table 2). The 3D seismic survey full-stack data is used in the given 3D seismic surveys.

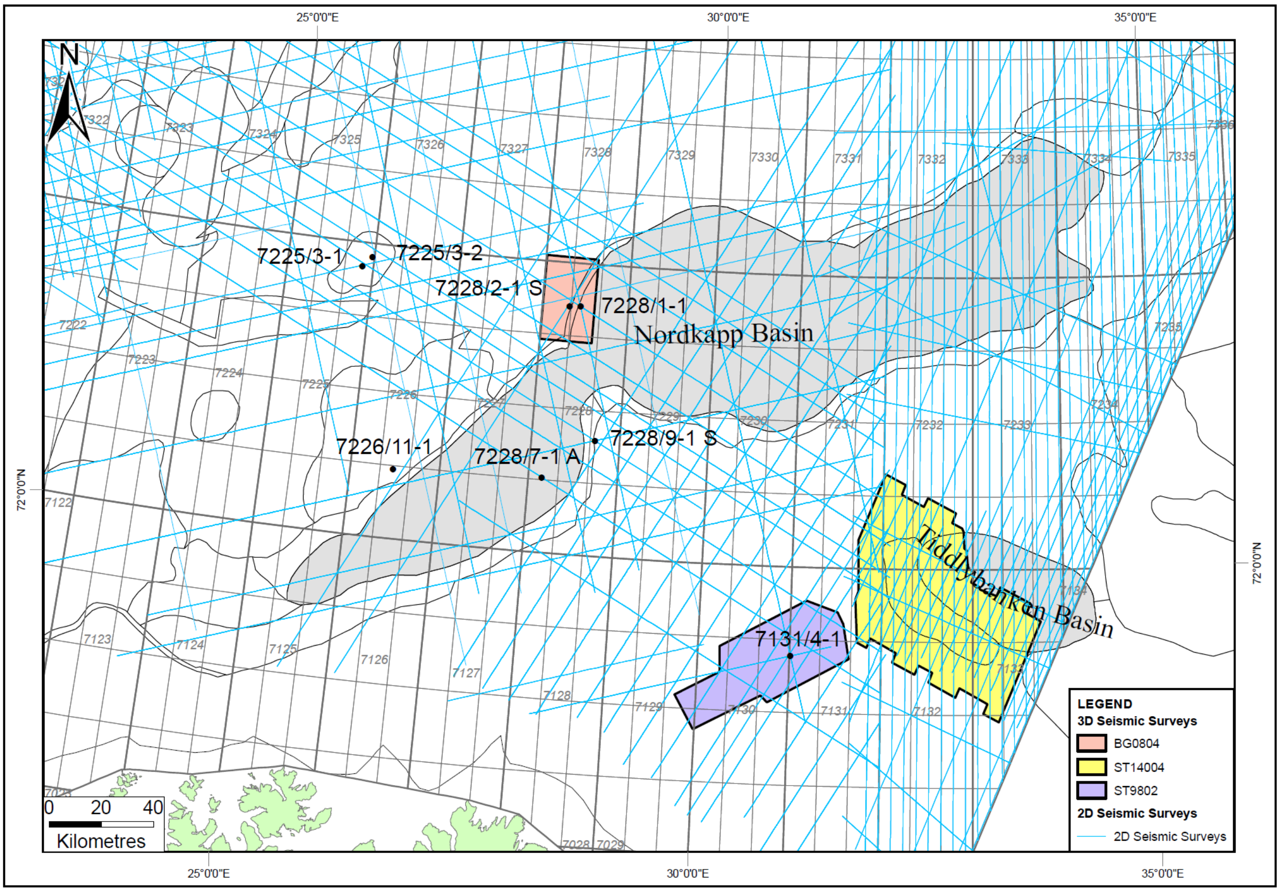


Figure 5: Overview of the selected 3D seismic surveys (BG0804, ST14004, ST9802), key wells and available 2D seismic surveys.

The quality of the 3D seismic data is considered good in all the cubes. The survey covering the Tiddlybanken Basin is of especially good quality, as it is a new broadband with wide frequency range. The general characteristics of the surveys are SEG reverse polarity (European polarity/negative standard polarity) and zero-phase. In some cases there is some phase rotation of the (zero phase) wavelet.

There is a large amount of available 2D data and the quality is ranging from poor to good, with poorer quality often found in areas around and adjacent to salt diapirs and in the older surveys. The polarity and phase vary in behavior from survey to survey. However, this has been accounted for when working regionally.

3D Seismic data coverage			
Location	**Tiddlybanken Basin**	**Nordkapp Basin**	**Finnmark Platform**
Survey number	ST14004	BG0804 (Eik)	ST9802 (Gouvca)
Wellbore	none	7228/2-1S and 7228/1-1	7131/4-1
Size (km^2)	5450	615	1500
Year	2014	2008	1998
Polarity	SEG reverse polarity	SEG reverse polarity	SEG reverse polarity
Sampling interval (ms)	2	4	4

Table 1: Information regarding the 3D seismic surveys.

2D Seismic data coverage
NBR08
NBR09
NBR12
NPD-BA-11
NPD-1201

Table 2: 2D seismic data coverage over the southeastern and central Barents Sea.

3.1.2 Well data

The well data included in the thesis is mainly focused around the interest areas. The key wells used are located on the platform area of the Finnmark Platform (wellbore 7131/4-1) and northeastern part of the Nordkapp Basin (well 7228/1-1 within the basin and 7228/2-1S on the flank) as seen in Figure 5. Well tops and calibrated well-ties were provided by A/S Norske Shell. Table 3 summarizes the well data information. The purpose of the other wells was to extend the understanding of the regional behavior and extent of the depositional systems. The wells have been selected to:

- provide information on the Snadd Formation gross strata;
- understand the Snadd Formation mega-sequence;
- identify Snadd channel types and their spatial and stratigraphic distribution and variability; and
- calibrate for fluvial styles and architecture inferred from seismic data.

Well data information						
Structural elements	**Well**	**Operator**	**Year**	**Total depth (m MD)**	**HC in Snadd Fm**	**Thickness of Snadd Fm (m)**
Nordkapp Basin	7228/1-1	Norwegian Energy Company	2012	1714 (Kobbe Fm)		376
Nordkapp Basin	7228/2-1S	Mobil Development Norway	1989	4300 (Havert Fm)		915
Nordkapp Basin	7228/7-1A	Statoil	2001	2881 (Klappmyss Fm)	x	613
Finnmark Platform	7131/4-1	Statoil	2005	1295 (Kobbe Fm)		212
Norsel High	7226/11-1	Statoil	1987	5200 (Basement)		582
Norvarg	7225/3-1	Total	2011	4150 (Isbjørn Fm)		718
Norvarg	7225/3-2	Total	2013	2210 (Klappmyss Fm)		710

Table 3: Well data information.

Core database of Snadd Formation

Core material from the Snadd Formation has been inspected from 7131/4-1 and 7228/7-1 A wells (Figure 5). The 7131/4-1 well has core samples from the Late Snadd and Lower Snadd stratigraphic sequences that have been inspected. Wellbore 7228/7-1A from the Lower Snadd sequence has been briefly studied to get an understanding of the fluvio-deltaic systems of the Snadd Formation. The cored interval information is listed in Table 4.

Well	Cored interval (m)	Formation	Second-order seq.
7131/4-1	915 - 944.1	Snadd	Upper Snadd
	1070 - 1117.9	Snadd	Lower Snadd
7228/7-1 A	2059 - 2103	Snadd	Lower Snadd

Table 4: Core database inspected and included in the thesis.

3.2 Methodology

The 2D seismic data has been utilized for a regional interpretation within and around the Nordkapp and Tiddlybanken basins, providing a semi-regional understanding. Emphasis has been on the Triassic Snadd Formation. On this part of the Barents Sea the 3D seismic data was used to interpret the selected salt basin examples with variation in creation of accommodation space, spatial/temporal style of infill patterns, and fluvial styles identified in salt basins/mini-basins.

Mapping of salt bodies, faults, analysis of seismic data and thickness maps helped to achieve a better understanding of the salt timing and styles of salt structuring halokinesis to understand the semi-regional to regional tectonic setting. The regional 2D seismic dataset was mapped to understand the regional structures and this was integrated with regional studies from Glørstad-Clark et al., 2011, 2011; Klausen, 2013; Klausen et al., 2015; and Riis et al., 2008. The 2D seismic dataset was used to establish the tectonic setting and to develop an understanding of the structural evolution of the salt basins. Furthermore, it was used to analyze the role of the regional tectonic events and/or sediment loading on both the creation of accommodation space, and the triggering mechanism for the salt initiation.

Fluvial seismic characters were identified through amplitude variations and evaluating fluvial reservoir types, fluvial architecture and facies in the seismic data. Available well and core data is studied and integrated with the seismic data and incorporated in the thesis, in addition to analogue data.

3.2.1 Stratigraphic framework literature review

This thesis focuses on the Triassic Snadd Formation, and describes the spatial and variability of fluvio-deltaic sequences in reaction to salt diapirism in selected mini-basins in the Barents Sea. Earlier, workers such as Glørstad-Clark et al. (2011) and Klausen et al. (2015) have established a stratigraphic framework of this region. According to Glørstad-Clark et al. (2011), the Snadd Formation consists of mainly two second order stratigraphic sequences bound by maximum flooding surfaces (MFS), and is furthermore subdivided into third order sequences (Figure 6). The principle of using MFS as bounding surfaces for stratigraphic intervals was proposed by Galloway (1989). Stratigraphic refinements of the Glørstad-Clark et al. (2011) study are used in the sequences by Klausen et al. (2015). Klausen et al. (2015) identified several third-order sequences and provided a correlation of the stratigraphic sequences towards Svalbard. Additional information about this is in section *5.0 Stratigraphic Framework*.

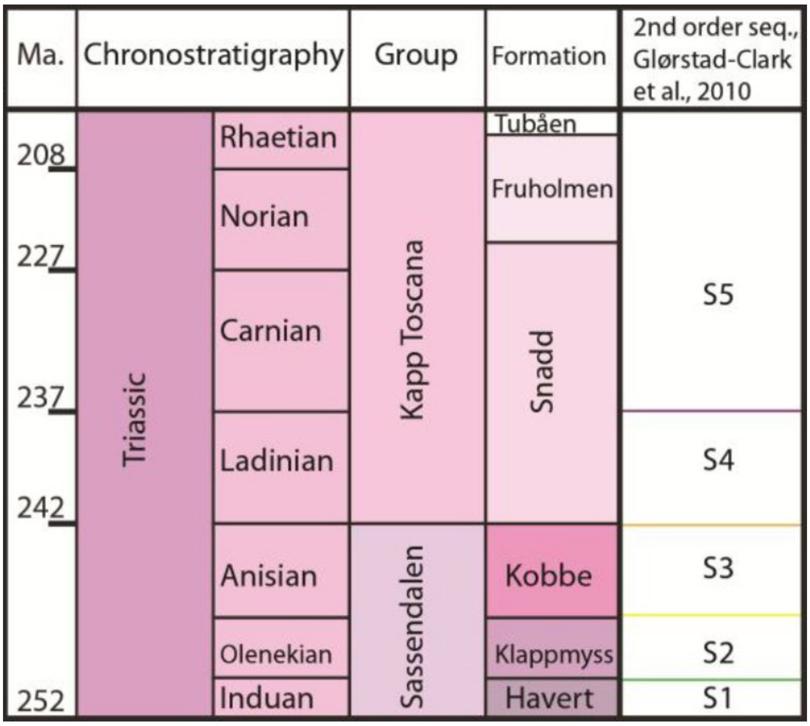


Figure 6: Triassic lithostratigraphy with second–order sequences defined by Glørstad-Clark et al. (2010) from (figure from Klausen (2013)).

3.2.2 3D Multi-attribute workflow to identify stratigraphic mini-basins

The seismic interpretation was carried out using mainly Petrel 2014© by Schlumberger. A/S Norske Shell provided regional maps and interpretations (with various quality) in the interest areas. These are taken into account, and this project is seen as a continuation of the work already done in the company. In order to get a dense set of well-trusted interpretations, quality control of previous work and supplement interpretation have been performed.

The following seismic interpretation workflow/approach was used to characterize and define and identify the mini-basins (Figure 7). The first step was to do preconditioning of the 3D seismic data, by using the Volume attribute in Petrel 2014©. Voice band pass filter and Van Gogh filter were applied to the cubes. The next step was to use seismic interpretations to constrain the model, creating multiple new interpretations in Shell´s plugin software, Stratascan. The software produces high resolution, detailed interpretations on every stratigraphic level, allowing extraction of seismic horizons in a specific time interval. With the use of this software, individual parts of the cube are interpreted and these need to be manually interpreted and connected before continuing to extract the final surfaces. Key reflectors capturing flooding events and fluvial styles were the main targets, which were intended to be used to understand the infill patterns and evolution of the mini-basins through time. The third step was to generate seismic extraction attributes in Shell´s proprietary interpretation platform GeoSigns, in Linux, using Trap Search Engine (TSE) after carefully selecting reflectors of interest. The TSE extracts several attribute maps for a given stratal slice simultaneously. Attributes include peaks, troughs, maximum amplitude, in combination with Spectral Decomposition of the 3D seismic data created by A/S Norske Shell. A search window of 10 to 20 milliseconds was used to evaluate the specific stratal slices during the analysis. The extraction was performed on single reflectors (or in an interval between two trusted reflectors). The extracted amplitude variations show the presence of geological features on the specific stratigraphic interval in the attribute maps.

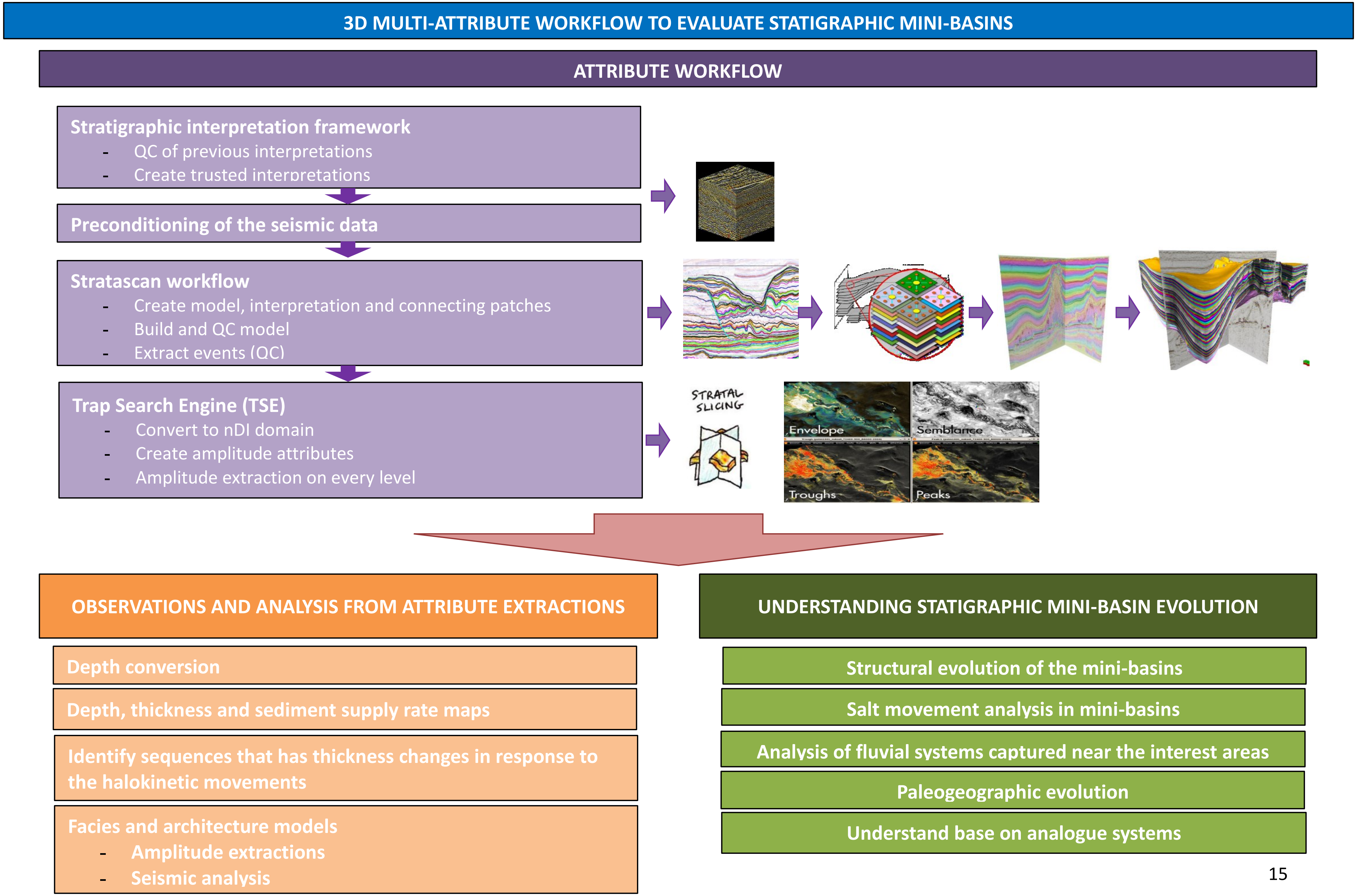


Figure 7: Workflow chart of the 3D multi-attribute attribute workflow to evaluate the stratigraphic mini-basins (illustrations used in the attribute workflow are provided in courtesy of Norske Shell).

4.0 Fluvial styles and concepts of halokinesis

The Triassic interval in the Barents Sea is dominantly consists of retrograding and prograding depositional cycles, and the depositional elements range from marine to fluvial (Glørstad-Clark et al., 2011, 2010; Klausen et al., 2015). These fluvio-deltaic systems have their own controlling mechanisms; however, salt tectonics also has an influence on the sedimentation in the study areas. Therefore, the main controlling factors are many, dependent on the type of alluvial system, sediment supply, creation of accommodation space and salt diapirism. These parameters have a direct impact on the architecture and stratigraphic evolution in the basin.

4.1 Alluvial systems

4.1.1 Controls and classification of alluvial systems

Braided, meandering, anastomosing and straight river systems are recognized as the four common channel systems. The discharge, gradient and sediment supply are the main controlling factors on channel pattern (Emery and Myers, 1996). Classification of river channels in a plan view involve studying the channel curvature (sinuosity) and the rivers ability to split (braided) the flow (Reading, 1996).

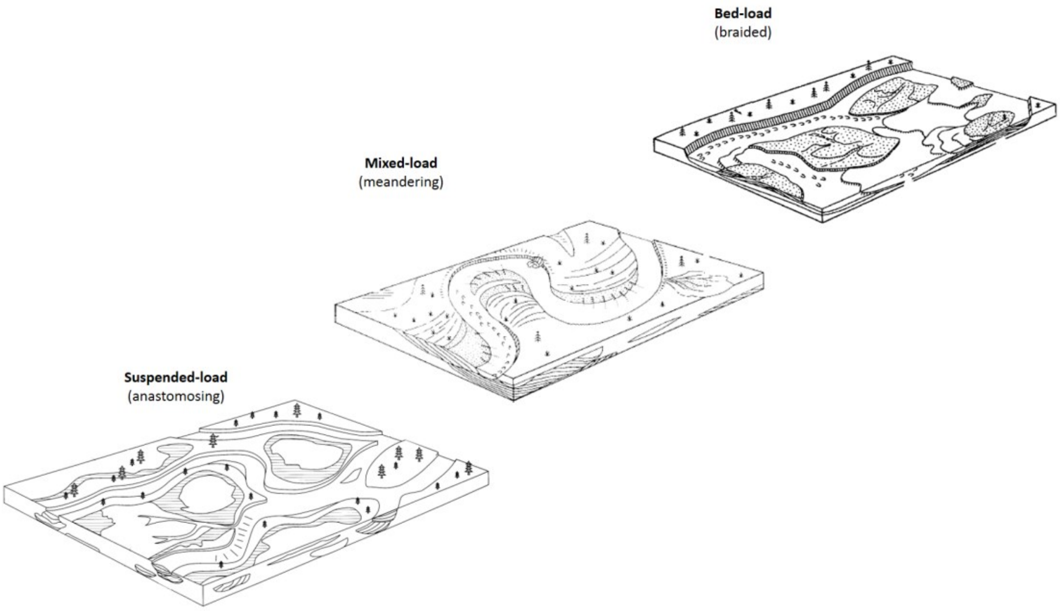


Figure 8: Overview of fluvial channel systems, illustrating braided, meandering and anastomosing channel styles (modified from Emery and Myers (1996)).

4.1.1.1 Suspended-load rivers

Anastomosing systems are characterized by having several interconnected and narrow channels with variable sinuosity separated by stable and vegetated islands (Figure 8). They are dominant in areas downstream with low gradient, stable banks, isolated and are composed of silt and clay carried in suspended load (Emery and Myers, 1996). As a consequence of the low gradient and amount of fine-grained material, they have a tendency to form stable channels and not migrate, but rather split and rejoin further down the river (Reading, 1996). Avulsion is normally the process that changes the course of these channels. These anastomosing systems are found in humid conditions and are dominantly in the coastal-plain environments with mud-filled channel features in the floodplain area (Emery and Myers, 1996; Reading, 1996).

4.1.1.2 Mixed-load rivers

Meandering channels consist of high-sinuosity channels on low-gradient alluvial and delta plains (Figure 8). Modern high-sinuosity channels carry variable grain-size material, predominantly as suspended load with the coarser fraction of the bed-load (Emery and Myers, 1996). In meandering rivers, point bars are created at the inner bend as the fluvial system is migrating laterally (Emery and Myers, 1996; Reading, 1996). If the system migrates until it reaches the bank-full level, concentric and elongated ridges can be created due to lateral accretion of sediments, creating scroll bars. The channel changes course by avulsion, e.g. after flooding, the channel bank can become breached (Reading, 1996). As defined by Schumm (1977), the sinuosity of mixed-load rivers is expected to be ~1.5.

4.1.1.3 Bed-load rivers

Moderate to strong braiding occurs in coarse-grained bedload streams with low sinuosity (Emery and Myers, 1996; Reading, 1996) (Figure 8). As a result of the river being overloaded, it might start to braid (e.g. because of gradient reduction). The braided style appears once deposition of sediments accumulate on the channel floor, splitting the flow. Depositional elements associated with coarse-grained bedload rivers are traverse and longitudal bars. In sandy-rich bedload river systems the sinuosity is fairly low. Though braiding is well developed compared to the coarser counterparts, it consists of fewer separated channels and some meanders. One of the major controlling parameters in the braided systems is the available abundancy of sand (Reading, 1996). Based on Schumm (1977) the expected sinuosity of bed-load rivers are ~1.

4.2 Salt Tectonics

Salt are a common feature in many sedimentary basins and are a part of the stratigraphic column. Rock salt consists mainly of halite (Hudec and Jackson, 2007). The salt properties are different from siliciclastic rocks, and have a quite low density (of 2,160 g/cm^3) (Fossen et al., 2010). The triggering mechanisms for salt diapirism include differential loading, involving lateral variations of the overlaying strata´s density, thickness and weight (Hudec and Jackson, 2007; Jackson, 1995). Salt movement may be induced by gravitation, thermal gradient or displacement loading. A secondary mechanism is buoyancy which was believed to be the controlling factor for a long time (Hudec and Jackson, 2007). The impermeable and nonporous salt will start to rise as the overburden becomes compact and denser than the salt (Fossen et al., 2010; Van Der Pluijm and Marshak, 2004). Salt movements deform the overlaying sequences as the salt flows like a viscous fluid, creating various salt structures and geometries (Van Der Pluijm and Marshak, 2004). Diapirism is often related to regional tectonic events that causes the weak salt to force its way upwards, leading to deformation and faulting. This means that tectonic events and salt movement creates topographic highs and lows. This leads to syn-halokinetic accommodation creation and subsequent thinning and thickening sequences in the basins due to salt tectonics (Hudec and Jackson, 2007).

4.2.1 Diapiric growth

Salt expulsion is a result of sediment loading, forcing the salt to move into the diapir from its source layer (Hudec and Jackson, 2007). There are two types of salt structure growth processes, named upbuilding and downbuilding. The upbuilding process (or active diapirism) involves salt rising after deposition of strata above, resulting in salt breaking through the overburden (Van Der Pluijm and Marshak, 2004). Downbuilding (passive diapirism) occurs once the diapir rises constantly, is close to the surface (or at the surface) and sediments are accumulating around the diapir. The shape of the diapiric structure and sequences are determined by the relationship between the sediment aggradation and diapir rise rate (Figure 9) (Fossen et al., 2010; Hudec and Jackson, 2007; Van Der Pluijm and Marshak, 2004). Reative diapirism is a response to regional extension that weakens the overburden, making it possible for the salt to rise into the thinning overlaying sediments. Once the salt is less dense than the overburden, the buoyancy and gravitation force the salt to rise and break through the sediment roof, often resulting in a passive diapir (Hudec and Jackson, 2007). Faulting is associated with salt movement as the weak salt is considered a good glide horizon. In some cases, it can create listric faults, as the faults detaches and sole out in the salt (Van Der Pluijm and Marshak, 2004). The shapes of salt structures are illustrated in Figure 9.

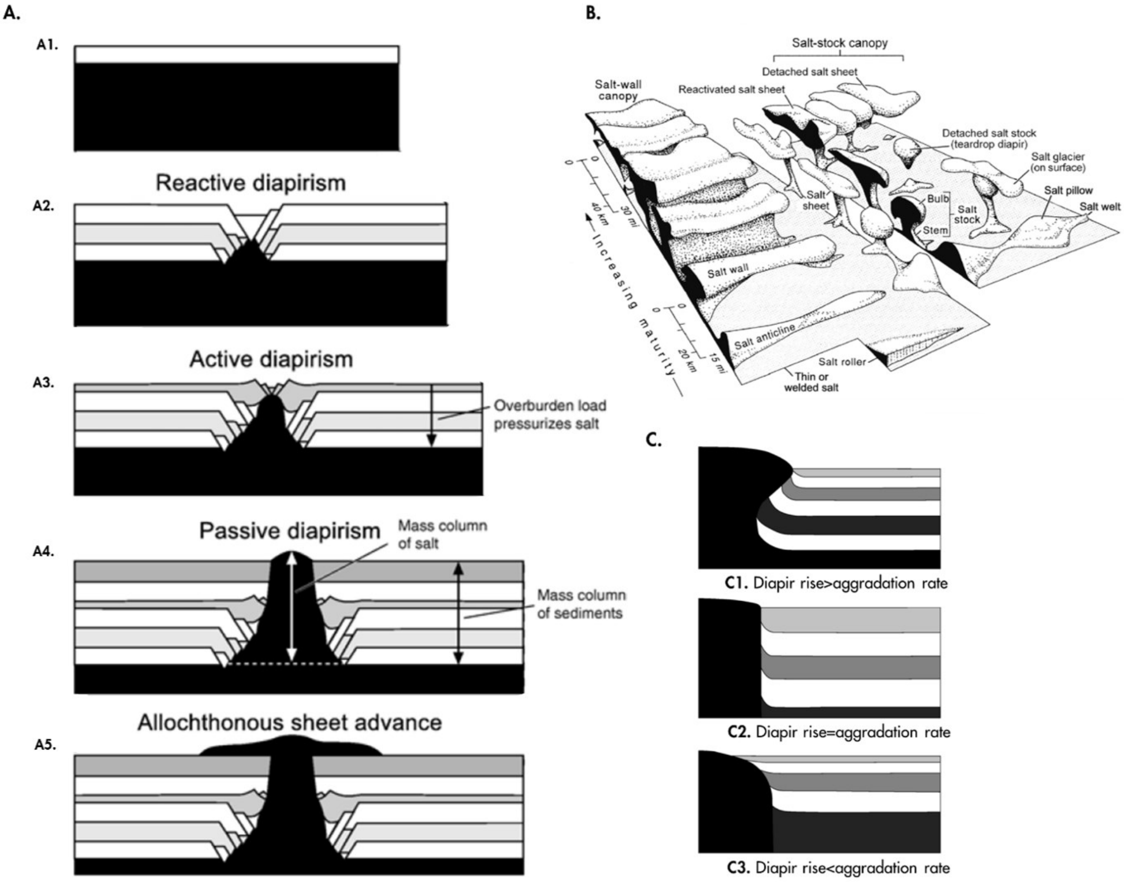


Figure 9: A) Illustrates a general regional extension with diapir piercement (however, it does not neccesarily to go through all the steps), B) Illustrates different salt shapes and C) Conceptual model of passive diapir rise and sediment aggradation, where: C1) is when the diapir rise is greater than aggradation rate; C2) when diapir rise is balanced with aggradation rate; and C2) when the aggradation rate exceeds the diapir rise (modified after Hudec and Jackson, 2007).

4.3 Salt-walled mini-basins and sedimentary infill processes and stratigraphy

Salt-walled mini-basins can occur in areas with the presence of these controls: (i) Sufficient salt layer thickness and (ii) an initiation mechanism for halokinesis (e.g. extension, differential loading or buoyancy) (Banham and Mountney, 2013b).

4.3.1 Controlling parameters in mini-basins

Both static (e.g., original thickness salt of layer) and dynamic (e.g., sediment delivery and climate) parameters are known to influence the style of sediment distribution in salt mini-basins (Banham and Mountney, 2013b). Eustasy and tectonic subsidence and uplift act independently of one another, but the relative sea-level fluctuations are controlled by these two parameters (Coe et al., 2002). Together the eustasy and subsidence rate control the creation of accommodation space (Emery and Myers, 1996). The relative sea-level fluctuations account for the local eustatic sea-level changes in addition to the tectonic events in that area. Change in the relative sea-level results in an increase or decrease in accommodation space in a marine setting. Furthermore, the eustatic sea-level can be falling at the same time as the relative sea-level rises, with a higher subsidence rate than the falling eustatic sea-level (Coe et al., 2002).

4.3.2 Sedimentary infill and sequence stratigraphy

4.3.2.1 Accommodation filling

Complete filling of accommodation is possible when abundant amounts of sediments are supplied to the basin. As the sediment influx rate is not spatially and temporally constant, some variations are considered in the following paragraphs. A balance between the sediment influx and relative sea-level decides if the facies belts are moving basinward (regression) or landward (transgression). With zero amount of accommodation space, the system will prograde and sediments by-pass to another location with available accommodation space. In the case of negative accommodation space, the system will erode the previously accumulated deposits and move the sediments to an area with positive accommodation space. Sediment compaction will additionally increase the accommodation space (Coe et al., 2002; Embry and Myers et al., 1996).

With a seaward shift of the shoreline, the constant rate of sediment influx is greater than the topset accommodation volume and the fluvial system progrades (deltaic extension). The facies belts will then start to move basinward due to the regression. Retrogradation (backstepping) of parasequences is a result of a landward relocation of the shoreline, a consequence of a greater increase in accommodation in the topset accommodation volume in comparison with the constant low rate of sediment influx. In this case the facies belts migrate landwards because of the transgression. In situations where moderate sediment supply rate is equal to the accommodation space, the shoreline location remains stationary, with an aggradational stacked pattern. Under such conditions the coastal-plain facies accumulate and is vertically stacked with excess sediments bypass into the basin. With decreasing accommodation, older sediments could be exposed and eroded during relative sea-level fall (Coe et al., 2002; Emery and Myers et al., 1996).

4.3.2.2 Sediment supply

How and where the sediment fill the accommodation space is controlled by the sediment supply rate (Emery and Myers, 1996). The sediment supply is mainly controlled by tectonics and climate. The tectonic regime will control the area of exposure (e.g. regional uplift and local faulting) and lead to a higher gradient with higher resultant sediment supply. Climate can impact the sediment supply rate because precipitation and temperature variations have an effect on hinterland erosion rate as well as the resultant transportation systems (Coe et al., 2002). The morphology of the sequences will change depending on the amount of sediment supply. In an extreme case with no sediment supply, no deposition of sediments will occur regardsless of the relative sea-level activity. In contrast, with a high sediment supply rate the accommodation space will fill quickly, and the system will continue to prograde. Normally, during a relative sea-level rise, the rate of clastic material will drop as more continental areas become submerged and vice versa (Coe et al., 2002).

4.3.2.3 Seismic sequence stratigraphic framework

Interpretation of seismic data makes it possible to identify depositional sequences, define stratigraphic framework and genetic depositional packages and evaluate the structural evolution of the study area. By analyzing the stratal termination relationships, such as onlap, downlap, toplap and truncation, it is possible to gain information about the depositional sequences and boundaries (Figure 10). Seismic facies analysis, including amplitude, continuity, reflection geometry and frequency, are used to identify facies associations and packages and predict its lithology (Vail and Mitchum, 1977).

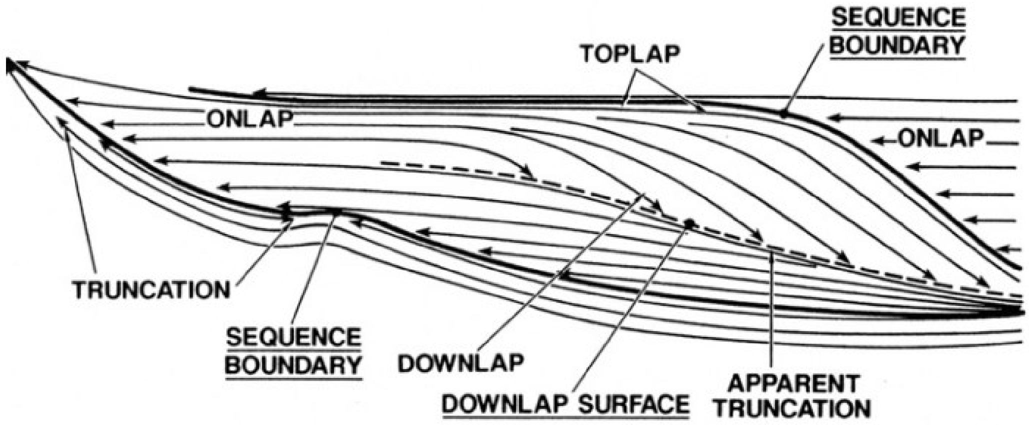


Figure 10: Reflection termination patterns and discontinuities from Vail (1987).

4.3.3 Fluvial and salt interaction

Triassic Snadd Formation is recognized by Klausen et al. 2015 as a fluvio-deltaic system. As this thesis is focused in areas affected by salt growth through Middle to Late Triassic, there will be resultant interplay between the sediment supply and accommodation creation (due to salt movements).

During salt wall growth and subsidence, rim-synclines are created, which will have a direct impact on the fluvial drainage system. As more sediments accumulate in the mini-basin, the differential loading increases, leading to enhanced salt withdrawing beneath to the adjacent salt wall, which in turn creates additional accommodation space (Banham and Mountney, 2013b). As a result, these topographic lows can be occupied by fluvial systems along the rim-synclines (Banham and Mountney, 2013b) and in turtle-back structures (Barde et al., 2002). The topographic lows and highs created by the salt movement, control the location, orientation, behavior, style of the transportation systems. As these packages thin and thicken as a result of salt movement, it will lead to further differential compaction that will drive the salt movement. Furthermore, the sedimentation location might shift to another depocenter, leading to grounding of the supra-salt stratigraphy as the salt structure drains (Van Der Pluijm and Marshak, 2004).

In salt (mini-) basins the fluvial drainage pathways are a result of the combination of sediment supply, subsidence (accommodation space), and salt-wall growth. The interplay can cause isolated basins or neighboring mini-basins, with reworking of uplifted salt walls and redistribution of the sediments. The relationship between the rate of sediment supply and subsidence determines the basin infill style, resulting in a filled basin, overfilled basin or underfilled basin. The mini-basins can be partially closed and occupied by underfilled lacustrine environments and fed from another system such as a delta (Banham and Mountney, 2013b). Banham and Mountney (2013b) conclude that overfilled basins can be a result of high sediment supply rate and accumulation that is equal or exceeding the rate of mini-basin subsidence and salt-wall uplift. This allows the fluvial systems to flow undisturbed, which creates the possibility that several mini-basins can be correlated within the basin (Banham and Mountney, 2013b).

5.0 Stratigraphic Framework

5.1 Previous established stratigraphic framework

Recent publications have established the stratigraphic framework of the Triassic Snadd sequences. The terminology of sequence stratigraphy in the area is described by Glørstad-Clark et al., 2011, 2010; Klausen, 2013; Klausen et al., 2015 (Figure 11 A) and B)). Klausen et al. (2015) has built the stratigraphic framework based on Glørstad-Clark et al. (2011, 2010) using the defined bounding MFS by Galloway (1989). The study method of Glørstad-Clark et al. (2010) consists of identification of stratal termination, disconformities and internal seismic facies in the seismic data. Two second order units (S4 and S5) are found in the Snadd Formation, separated by traced regional MFS and characterized by downlapping strata termination and landward shift of depocenters (Figure 11 A) and B)). Within these sequences, there are captured additional third order sequences (Glørstad-Clark et al., 2011, 2010). Klausen et al. (2015) subdivides the Snadd Formation a little differently, but builds the stratigraphic framework on the same principles as done by Glørstad-Clark et al. (2011, 2010). The Snadd Formation is sub-divided into a lower and upper part (S4 and S5), with Klausen interpreting sequence S4 to have existed for a longer period of time, and subsequently S5 to have existed for a shorter period of time, than Glørstad-Clark et al. (2011). Through identified semi-regional MFS, these successions are further divided by third order surfaces following the same hierarchy as mentioned above (Klausen et al., 2015) (Figure 11 B)).

5.2 Stratigraphic framework and well correlation

For the present study, the stratigraphic framework built by Glørstad-Clark et al., (2011, 2010), further developed by Klausen et al. (2015) and the MSF as bounding surfaces as proposed by Galloway (1989) has been used. Based on stratal terminations, seismic facies analysis, well data and attribute maps, this study is supporting the same stratigraphic framework as proposed by Klausen et al. (2015). Regional MFS are identified on top and base of the Snadd Formation. The Steinkobbe MFS is underlying the Snadd Formation, and marks the great landward shift of the shoreline. Two mega-sequences are identified, with up to three MFS separating the units, such as Early Ladinian top, top Lower Snadd (top E. Carnian) and top Upper Snadd (top L. Carnian to M. Norian). These findings are in agreement with the outcome of the investigation of Klausen et al. (2015) and a correlation is illustrated in Figure 11 (B). Figure 11 (C) illustrates the subsequent stratigraphic framework that will be used further in the thesis.

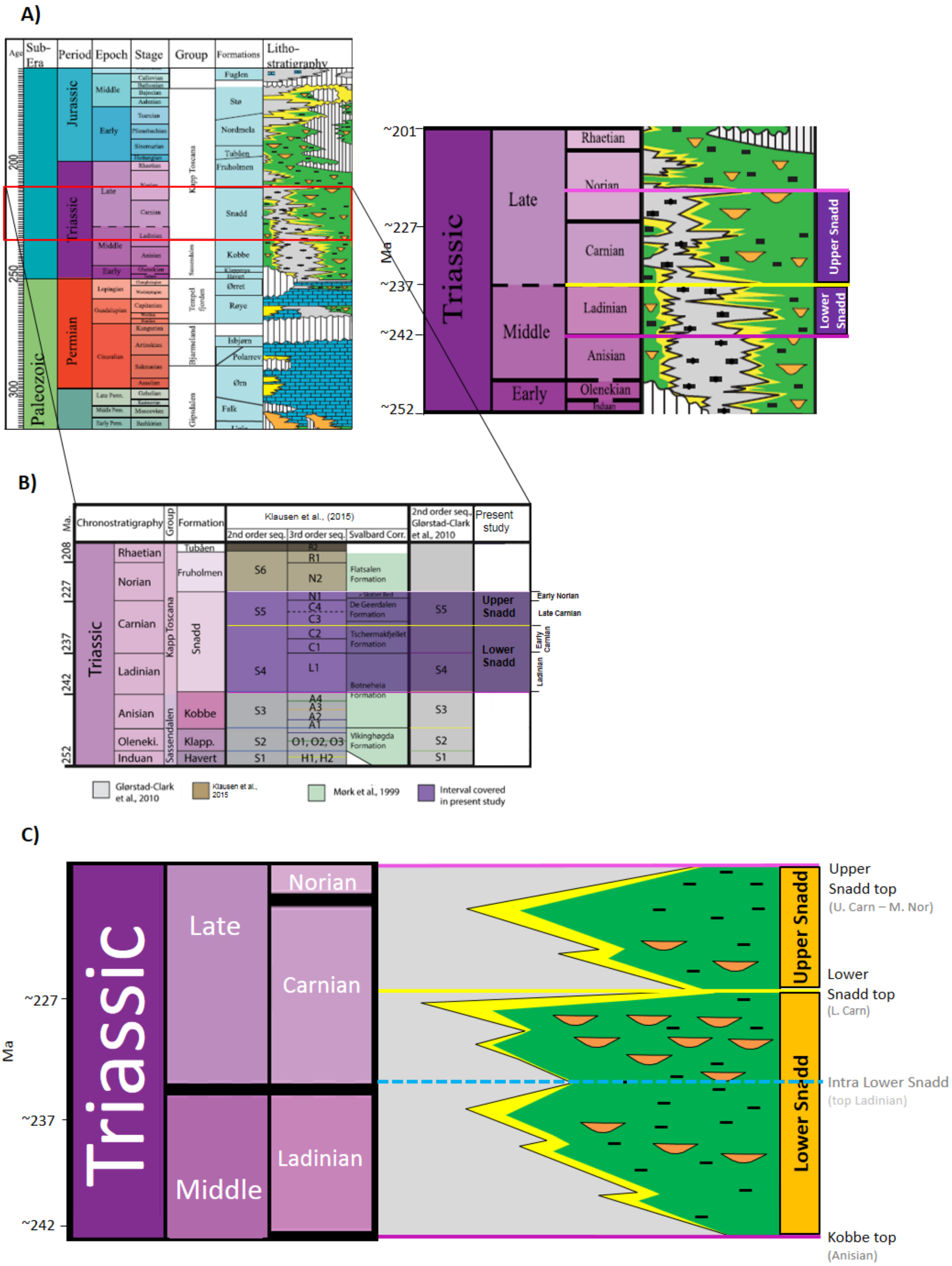


Figure 11: Stratigraphic framework presented by different workers, where A) is the lithostratigraphy defined by Clark et al. (2014) (figure from Clark et al. (2014)); B) comparison of second-order sequences by Klausen et al, (2015), Glørstad-Clark et al. (2010) and present study (modified after Klausen et al. (2015)); and C) Stratigraphic framework of present study, defining two mega-sequences (second-order) within the Snadd Formation.

Well correlation

Correlation between seismic and well data helps to provide an understanding of the regional fluvio-deltaic systems moving from the Finnmark Platform in the southeast, through the Nordkapp Basin and into the Bjarmeland Platform in the northwest (Figure 12). Key horizons are interpreted, including the Triassic horizons. The thickness around and adjacent to the salt diapirs are greater, which suggests that mechanisms as such salt tectonics, for example, can control the accommodation creation in the salt basins. Within the Snadd Formation, thickness variations occur and the seismic facies change vertically and laterally. There is identified a discontinuous and high amplitude facies belt in the Middle of Snadd Formation in the depocenters along the diapirs, that will be discussed in the study areas in the coming sections (Figure 12). This characteristic belt is partly existing on the platform areas as well. To better describe the Triassic Snadd Formation, the established framework will be used in the following sections.

The Triassic Snadd Formation with the established stratigraphic framework is displayed in Figure 13. The well correlation panel allows for a better understanding of the regional fluvio-deltaic style and architecture in salt mini-basins in comparison with the stable platform areas. The same thickening trends (as identified in Figure 12) is recognized in the well correlation, where there is a large growth of the Triassic Snadd Formation into the salt basins. This is dominantly identified in the Upper Snadd sequence and the lower part of Lower Snadd sequence.

The Lower Snadd mega-sequence in the lower part is dominated by shelf environment before the system starts to move basinward as the system progrades and is overlaid by coastal successions (Figure 13). The Lower Carnian package is interpreted to be sandy, and consists of abundant delta plain deposits, and fluvial channel-fills through the penetrated wells. The proximal 7131/4-1 well has preserved thick packages of fluvial deposits compared to other wells located on the platform areas. The sand bodies are thick, amalgamated and stacked. The amount of sand bodies decrease in the distal wells. The channels are in addition much thinner and show a less degree of amalgamation distally. Well 7229/11-1 only has fluvial channel fills in the lower part of the package. In well 7228/9-1S more sand penetrated, and the 7228/7-1A and 7228/2-1S wells consists of thick and amalgamated sands believed to be a part of a stacked multistory channel complex (Figure 13). The Upper Snadd sequence is interpreted to change from a shelf to deltaic and fluvial environment, before it was overlaid by deltaic and shelfal strata. As a result of regressive and transgressive cycles, the system shifts laterally and affects the lithology of the vertical successions. A similar pattern is found in both of the two mega-sequences. This is a result of shoreline position shifting through the Triassic Snadd, generating resultant progradational and retrogradational packages, which are mapped in Figure 13. These patterns will be further described and discussed in the following sections in the study. Available core samples from these packages (in wells 7131/4-1 and 7228/7-1A) are further discussed in section *7.3 Core Inspection,* and the location of the cores are indicated in Figure 13.

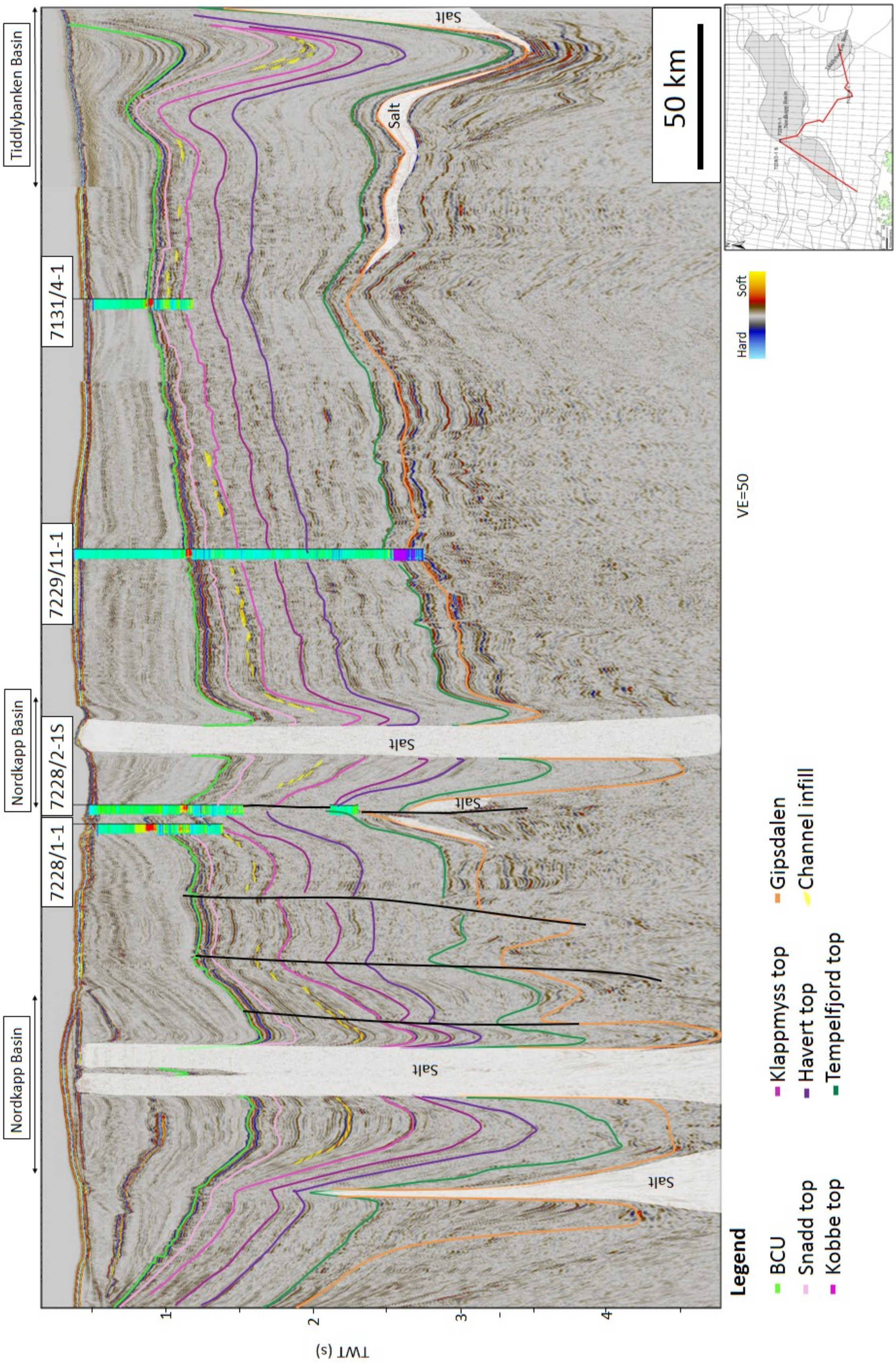


Figure 12: Seismic section with well correlation between Tiddlybanken and Nordkapp basins and Finnmark and Bjarmeland platforms. The channelized fluvial system in the Snadd Formation is outlined in the figure, and shows the presence of fluvial systems adjacent to the salt diapirs.

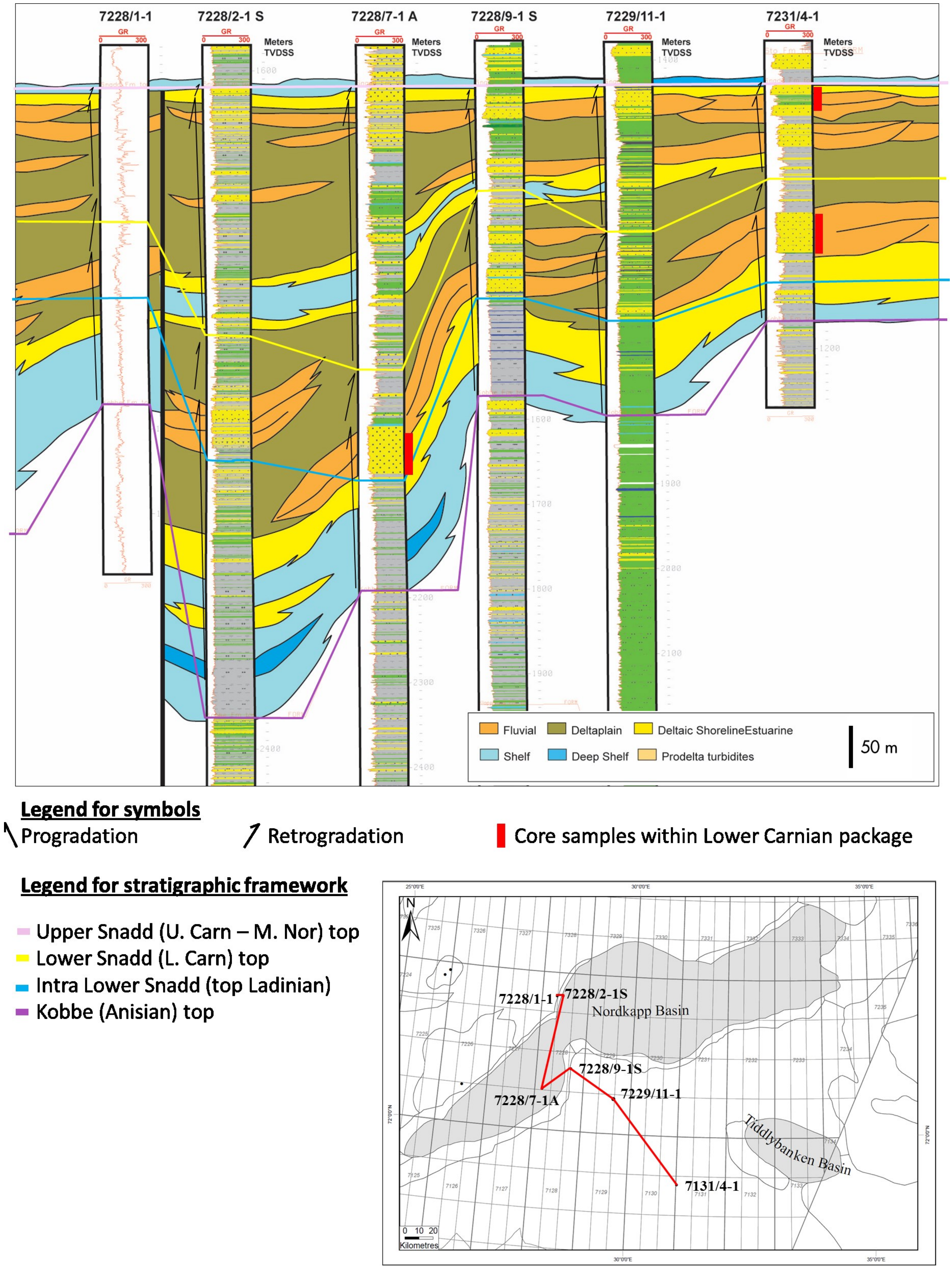


Figure 13: Well correlation between the southeastern Finnmark Platform, across the Nordkapp Basin to the Bjarmeland Platform. The interpretation of depositional environment is provided in courtesy of Norske Shell. Core data used in the present study are indicated in the figure, and will be further discussed in section 7.3 Core Inspection.

6.0 Structural evolution

The Triassic Nordkapp and Tiddlybanken basins are examples of salt-structured basins. Understanding the structural evolution of the basins is crucial to better understand the timing of subsidence and accommodation creation. The structural evolution of the Tiddlybanken and Nordkapp Basin is therefore described in detail with especially focus on the Middle to Late Triassic Snadd Formation. The structural evolution is discussed and illustrated with selected seismic sections and isopach maps. The study areas are hereby referred to as study area 1 (ST14004), 2 (BG0804) and 3 (ST9802), and the Greater Nordkapp Basin split into Southwest and Northeast sub-basins (Figure 14). The same figure shows the distribution of salt pillows and diapirs.

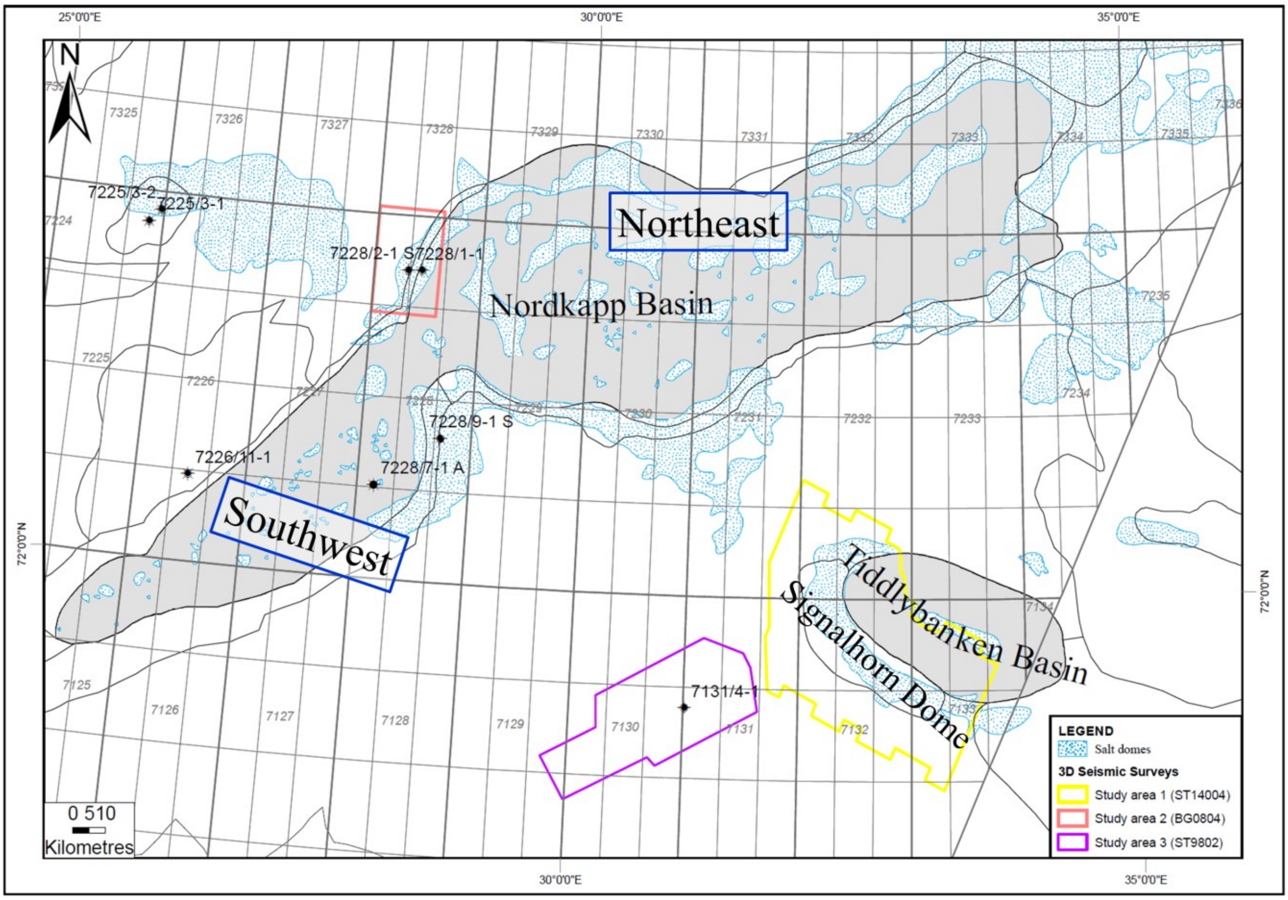


Figure 14: The map illustrates the location of study areas 1, 2 and 3 with sub-divided Nordkapp Basin into Southwest and Northeast sub-basins. The salt dome distribution is indicated in the map (cut on top Kobbe Formation) and are a mixture between salt diapirs and pillows (interpretation provided by Norske Shell).

6.1 Structural evolution of the Tiddlybanken Basin

The Tiddlybanken Basin has a strike orientation of northwest to southeast. The Signalhorn Dome is positioned along and parallel to the southwestern margin of the basin. In the center of the basin, a well-developed elongated salt wall and salt diapir is present with an approximate diameter of 23 km and 2 km (Figure 14).

6.1.1 Structural evolution of the Tiddlybanken Basin (Study area 1)

Based on analogy with the Nordkapp Basin and in-house studies provided by Norske Shell, the Tiddlybanken Basin started to form as a result of the rift-regime in the Late Devonian to Early Carboniferous times, and it was reactivated in Late Carboniferous to Permian. Through Carboniferous and Permian times, large quantities of salt were deposited in the basin (Figure 15). The Early Triassic (Havert Formation) was characterized by stable conditions with uniform subsidence. This is implied by the observation that the thickness of the sequence is relatively constant and there is no evidence of salt movement (Figure 15, F). Large deltaic systems were deposited on top of the Havert Formation. The thick packages of Lower Triassic strata (likely Havert and Klappmyss formations) on top might have triggered the initial rise of the salt pillow (Figure 15, E), activated by differential loading. Based on the flattened sections, the Signalhorn Dome, however, does not have any structural expression during the Early Triassic (Figure 15, E-F). The Middle Triassic (from Kobbe and partly Snadd formations) was a synkinematic interval, with an active diapir and salt wall growth (Figure 15, C-D). During Middle Triassic the salt pillow reached the seafloor due to salt piercement, causing uplift and erosion of parts of the Kobbe Formation (Figure 15, D), which has been deposited on top of the salt. Continued salt withdrawl, resulted in the creation of rim-synclines, increasing the subsidence and, therefore, creating accommodation space for a thickened Snadd Formation. In the earliest Late Triassic the salt has formed as a diapir piercing through the overburden, with adjacent rim-synclines alongside it (Figure 15, C). The Signalhorn Dome was at this time a ridge. The thickening of the Jurassic packages towards the salt diapir indicate salt withdrawing in the basin (Figure 15, B), and subsequent subsidence and deepening of the basin. This is the most significant diapir growth and deepening time in the basin. In Early Cretaceous, it is probable that there was simultaneous growth based on the adjacent lows and burial of the diapir. As evident by the seismic data, large volumes from Cretaceous to Neogene have been removed, and it is possible that there has been halokinesis phases further in time. The Signalhorn Dome was amplified in the Cretaceous to Neogene time (Figure 15).

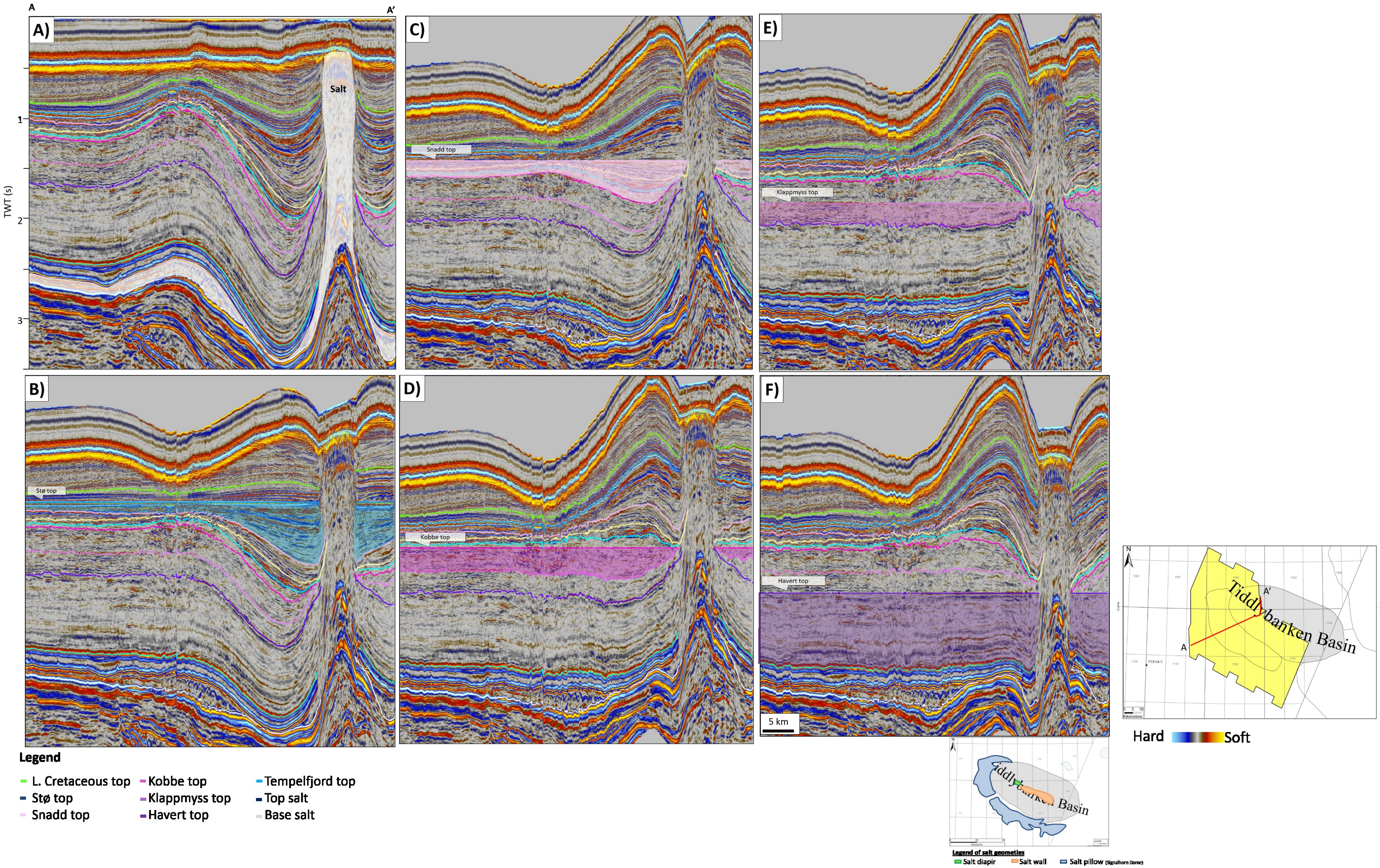


Figure 15: Several flattened sections of key reflectors are used to establish timing of halokinesis by identifying packages of growth or absence growth in rim-synclines.

6.1.2 Middle to Late Triassic (E. Ladinian – M. Norian) structural evolution of the Tiddlybanken Basin

The evolution of the Tiddlybanken Basin is described based on the established framework (*see section 5.0 Stratigraphic Framework*) consisting of Lower Snadd sequence (Ladinian and Lower Carnian) and Upper Snadd sequence (Upper Carnian – Middle Norian).

The Ladinian time is presented with slightly thickening sequences into the Tiddlybanken Basin. Compared with the underlying Kobbe Formation that experience diapiric growth, this interval shows thinning towards the northwest area of the Tiddlybanken Basin. There is no evidence of structural expression of the Signalhorn Dome, however salt evacuating to the elongated salt diapir and wall is creating some subsidence nearby (in the Tiddlybanken Basin). This is supported by the isopach maps of the Ladinian package, where the main depocenter is located along the salt wall in a northwest direction. (Figure 16 2 D)).

The characteristics of the Lower Carnian are rather distinguishable from the Ladinian strata. It is identified by reflectors onlapping the Signalhorn Dome and disappearing over the crest of the dome and additionally onlapping from the southwest. Early Carnian is dominated by growth of the Signalhorn Dome caused by uplift of an under-developed salt pillow. As a result of basin deepening as the diapir rises, initial and symmetric rim-synclines are developed adjacent to the salt wall and the diapir in the center of the basin. The Lower Carnian interval is deposited during salt-withdrawal, creating more subsidence in the salt mini-basin and subsequently accommodation space. In Figure 16 (C), within the mini-basin the reflectors are parallel and others thin out towards the diapir indicating that the salt piercement could have happened stepwise. That means that the salt perhaps has penetrated the overburden in repeating intervals. The shape of the salt diapir is relatively steep (diapir rise rate equals to aggradation rate), however there is an ambiguous breach in the salt diapir, related to passive diapirism where the diapir rise rate is less than the sedimentation rate. In the Lower Carnian isopach map there is identified a depocenter parallel to the Signalhorn Dome, located between it and the salt wall and diapir in the center of the Tiddlybanken Basin. It has an elongated shape and provides additional indications of salt diapiric growth (Figure 16, C).

The Upper Snadd interval display similarities with Lower Carnian. It has the same prominent features, such as the Signalhorn Dome ridge on the southwestern edge of the Tiddlybanken Basin and a salt wall and diapir in the center of the basin. The Late Carnian to Middle Norian time is dominated by passive diapirism. The exposure of the Signalhorn Dome is evident and the reflectors are pinching out towards the high (Figure 16, B). Along the western and eastern edge of the Signalhorn Dome, the sediments are thickening away from the ridge. It is identified a northwest (~20 km wide) depocenter in the Upper Carnian to Middle Norian isopach map, which indicates the creation of accommodation as a result of salt evacuation (Figure 16, B).

The development of the Tiddlybanken Basin has likely been affected by the Fedynsky High rifting in Triassic. Uplift of the Kola Monocline during this time, in addition to inversion on the Fedynsky High in Cretaceous to Cenozoic times, is expected to have an effect on the basin.

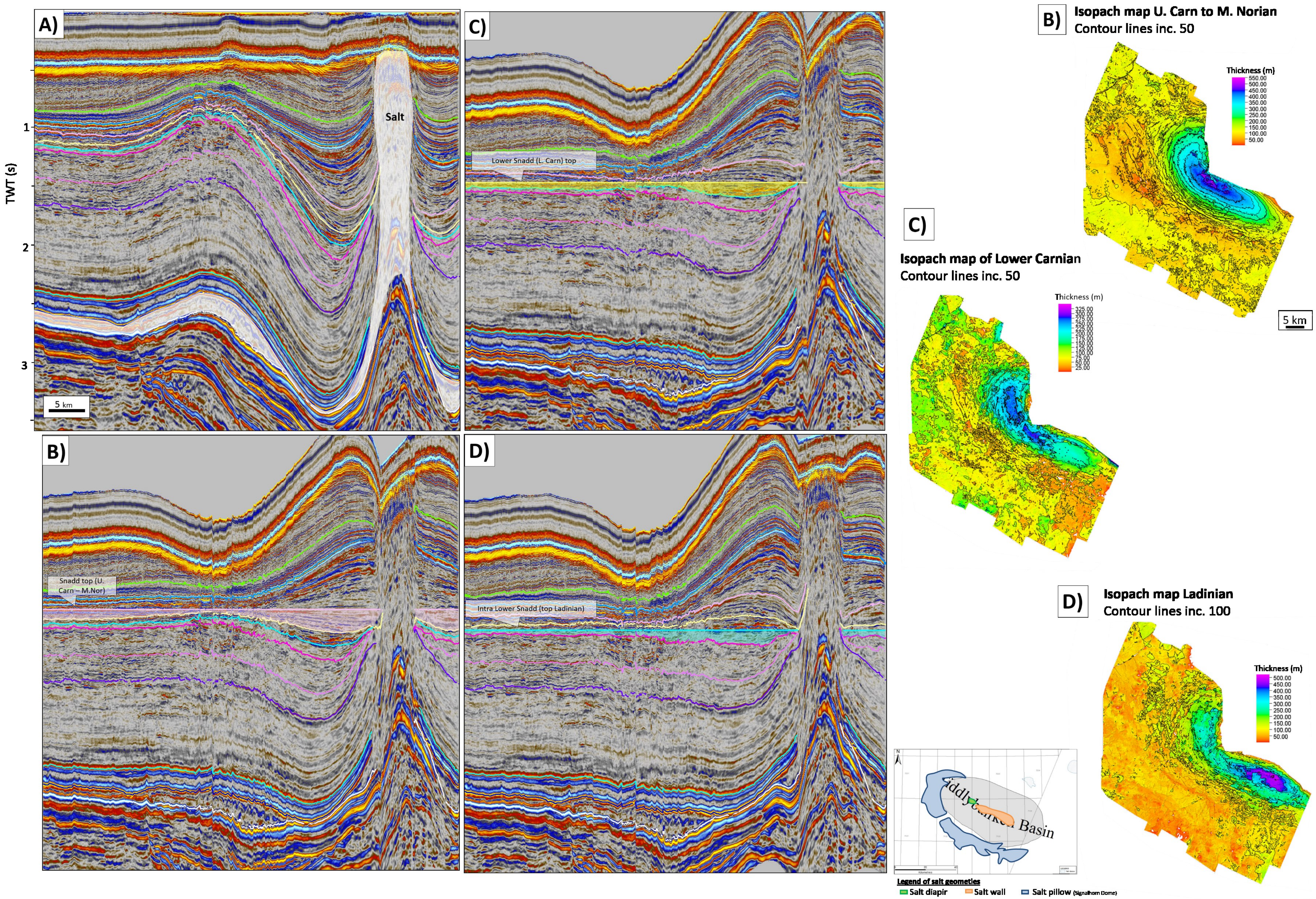


Figure 16: Several flattened sections of key reflectors are used to establish timing of halokinesis by identifying packages of growth or absence growth in rim-synclines in the Snadd Formation.

6.2 Structural evolution of the Nordkapp Basin

The Nordkapp Basin has a strike orientation of northeast to southwest. The basin is elongated and is recognized for its many salt diapirs. The central parts of the basin have well developed salt diapirs with different shapes, and the salt on the basin flanks are dominantly salt pillows. It involves unsynchronized salt movement at different stages in the basin. The Greater Nordkapp Basin split into Southwest and Northeast sub-basins (Figure 14) and is further described in this section.

6.2.1 Structural evolution of the greater Nordkapp Basin

To understand the semi-regional variability of the Triassic evolution of the Nordkapp Basin an evaluation is built on interpreted 2D seismic lines perpendicular to the strike orientation of the basin (Figure 17).

The Paleozoic Nordkapp Basin was created in Late Devonian to Early Carboniferous times, and during Late Permian times evaporates and salt in large amounts was deposited in the basin.

Northeastern Nordkapp Basin

In the northeastern part of the Nordkapp Basin minor diapiric growth commenced in the Early Triassic times, with quite uniform thickness at the flanks and thickening Havert Formation sequences in the central parts of the basin. At this time salt pillows were the dominant structures with constrained salt flow, and resulted in the formation of diapirs during Middle Triassic. The Middle Triassic Kobbe Formation is characterized by significant thickening into the sub-basin, and the development of rim-synclines (around diapirs) related to salt withdrawl basin during passive diapirism. The diapirs have slight overhang geometries, indicating that the rate of salt rise outpaced the sedimentation rate. During Middle to Late Triassic, the salt continued to move and created rim-synclines around diapirs in the central parts of the basin. Jurassic times are quieter and slightly deformed by salt tectonics (Figure 17 (green line)).

Southwestern Nordkapp Basin

The main thickening and thinning sequences associated with diapiric growth are observed in the Lower to Middle Triassic, mainly in the Havert, Klappmyss and Kobbe formations and to some extent also the Snadd Formation. The Lower to Middle Triassic units are subject to major diapiric piercement, creating withdrawl basins with a huge amount of salt evacuating to the diapirs. As a result, thick sequences terminate against the centrally placed diapirs. The Jurassic period show little evidence of salt diapirism with uniform thickness. (Figure 17 (orange line)).

Central Nordkapp Basin

The Lower Triassic Havert Formation is thickening into the basin and experiencing diapiric growth, creating associated subsidence along the salt pillows in the central part of the basin. The Klappmyss Formation seems to be relatively unaffected by salt tectonics. In the Middle to Late Triassic it is possible to identify packages that are slightly thickening towards the central part of the basin. However, the area is experiencing significantly less diapiric growth in the Middle to Late Triassic times, compared to what is observed in the Northwest and Southeast sub-basins. This studied 2D seismic line is fairly close to the boundary between the two sub-basins, and it has to be taken into consideration that it might not be representable for either of the sub-basins (Figure 17 (blue line)). Observed Triassic and Jurassic faulting can be a response to the salt removal and associated with creation of steepening topographic as rim-synclines are created along the diapirs.

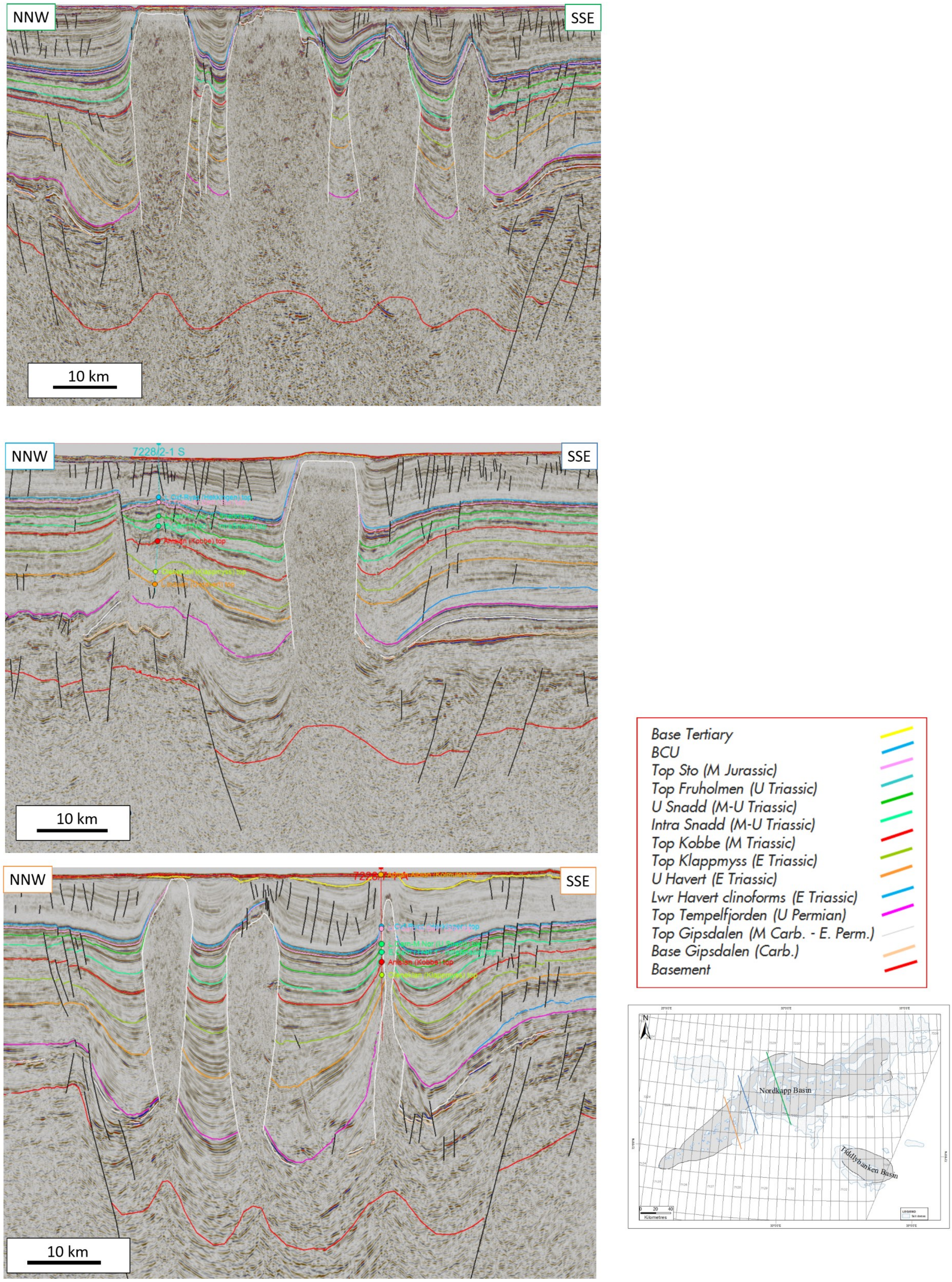


Figure 17: Several sections of key reflectors used to establish timing of halokinesis by identifying packages of growth or absence growth in rim-synclines (provided in courtesy of Norske Shell).

6.2.2 Northwestern part of the Nordkapp Basin (Study area 2)

6.2.2.1 Structural evolution of Nordkapp Basin in Study area 2

The Lower Triassic (Havert Formation) show quite uniform thickness, with no presence of salt piercement and stable conditions (prekinematic interval) (Figure 18, F). In the uppermost Lower Triassic (upper part of the Klappmyss Formation), there is slight initiation of salt movement (Figure 18, E), with thinning of the package towards the salt pillow. The main growth interval was during the Middle Triassic (Kobbe Formation), dominated by salt piercement. Kobbe Formation thin out towards the growing salt pillow on the northwestern Bjarmeland Platform and in the Nordkapp Basin (Figure 18, D). Middle to Late Triassic (Snadd Formation) was relatively quiet in the early stages in this part of the Nordkapp Basin. The Late Snadd is dominated by salt piercement, with activation of major normal fault(s) along the Nordkapp Basin margin, and as a result it is creating available accommodation space in the hanging wall (Figure 18, C). The Jurassic interval is filling available space in the hanging wall, making it possible for the creation of rim-synclines as adjacent lows in the Nordkapp Basin due to reactivation (or possibly continued ongoing faulting) during the Early to Middle Jurassic. By Late Jurassic to Early Cretaceous time, there is reactivation of the fault(s), based on the identified growth strata evidence in the hanging wall between the BCU and Stø Formation. As evident by the faulted overburden in the seismic section, it indicates a possible younger reactivation phase during Paleogene.

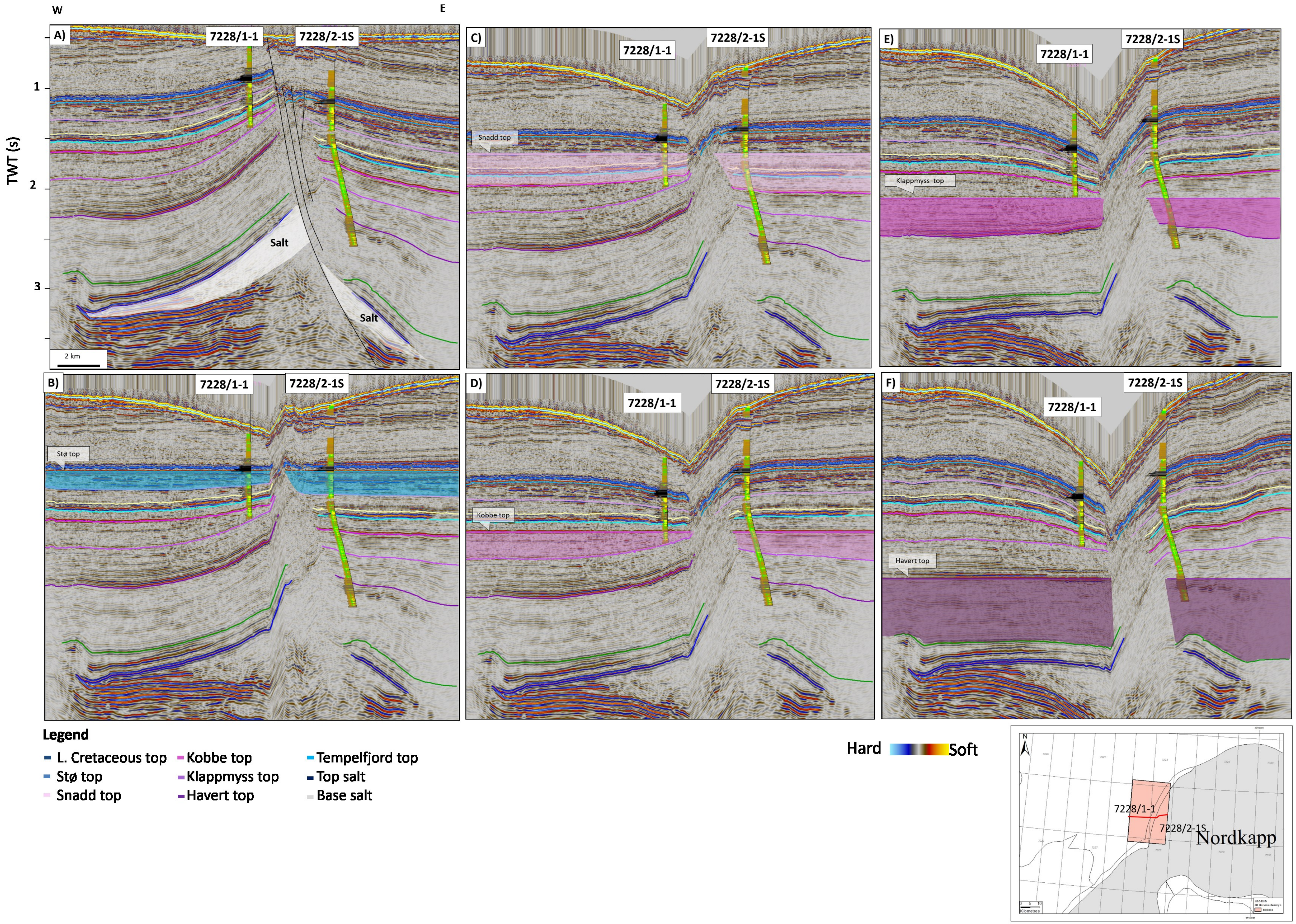


Figure 18: Several flattened sections of key reflectors are used to establish timing of halokinesis by identifying packages of growth in Study area 2.

6.2.1.2 Middle to Late Triassic (E. Ladinian – M. Norian) structural evolution of Study area 2

The evolution of Study area 2 of the Nordkapp Basin is described based on the established framework (*see section 5.0 Stratigraphic Framework*) consisting of Lower Snadd sequence (Ladinian and Lower Carnian) and Upper Snadd sequence (Upper Carnian – Middle Norian) (Figure 19).

The Ladinian interval has uniform thickness on the Bjarmeland Platform and in the Nordkapp Basin, though the hanging wall consists of a slightly thicker package. The Ladinian is interpreted to represent a period with no salt movement. However, previous salt tectonic has generated topography variations. There is identified two depocenters in the hanging wall, whereas the main depocenter is in the northeast, and a minor in the south. In the southwest, the depocenter has an elongated shape (Figure 19, D).

The Lower Carnian has a uniform thickness on the Bjarmeland and Nordkapp Basin. The Early Carnian is not affected by salt piercement and is signifying stable conditions. However, there is identified a major depocenter in the south of the study area, mainly in the hanging wall and partly in the footwall. Another minor depocenter is identified in the northeast of the hanging wall (Figure 19, C).

The Upper Carnian to Middle Norian sequence is affected by salt diapirism, with thinning of the northwestern package and increased accommodation creation in the hanging wall. Active piercement and associated features are dominating the halokinetic evolution in the L. Carn – M. Norian time. The salt pillow is growing, generating thickness changes of the interval. Associated with this, crestal faulting created a slightly listric normal fault(-zone). There is identified a depocenter in the southern part of the hanging wall up to 700 meters thick, that has been filled (Figure 19, B).

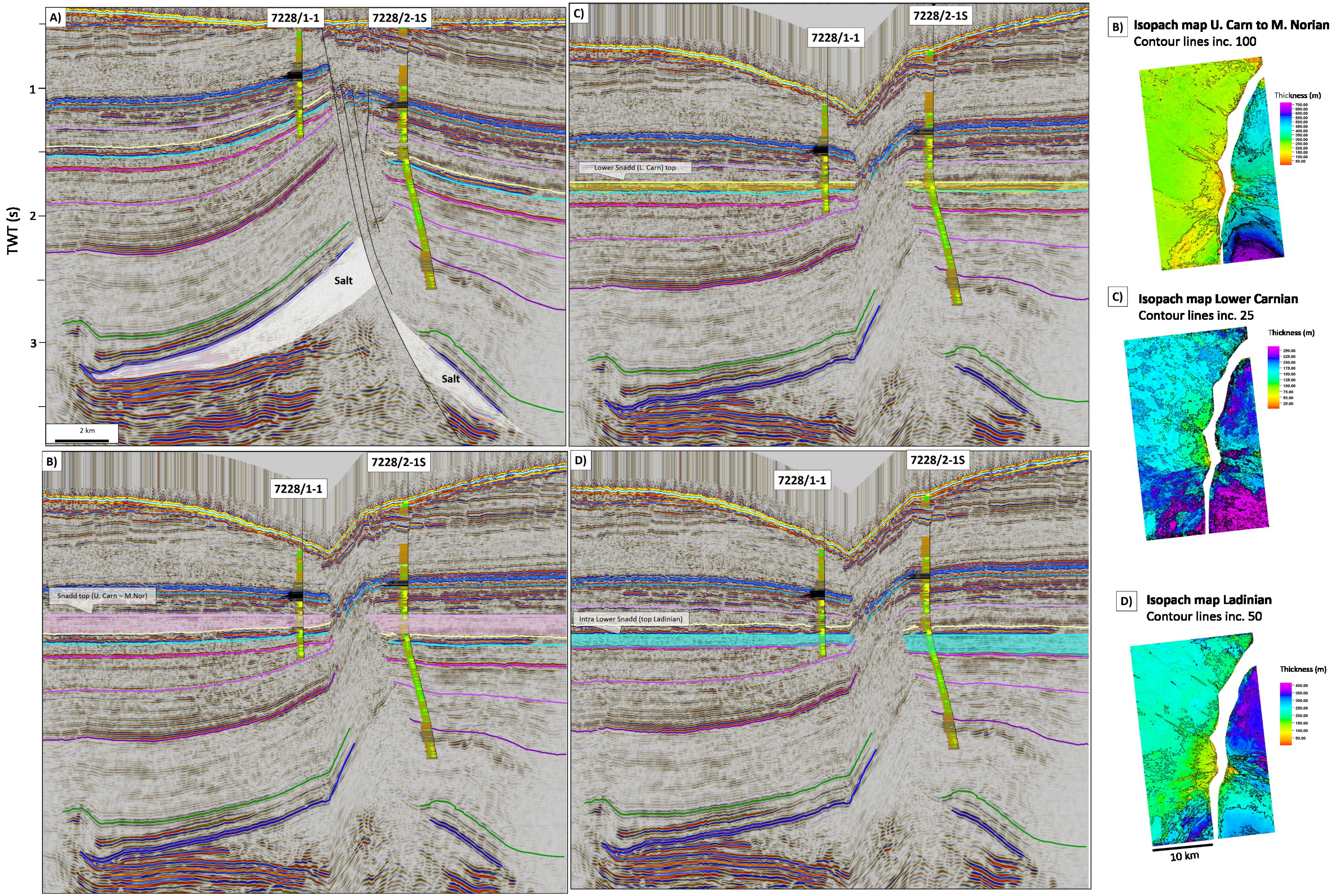


Figure 19: Several flattened sections of key reflectors are used to establish timing of halokinesis by identifying packages of growth or absence growth in rim-synclines in the Snadd Formation (Study area 2).

6.3 Comparison between Tiddlybanken and Nordkapp basins

As the Tiddlybanken and Nordkapp basins are salt-related basins, there are similarities between them. On the other hand, there are significant differences observed in relation to timing of salt movement and salt geometries.

The evolution of the basins remains similar, both mainly created in the Late Paleozoic times in response to rifting phases, with deposition of evaporites during Permian times. Timing of the salt movement is quite different in the two basins. The Tiddlybanken has its main diapiric growth interval in Middle Triassic to Jurassic times, whereas the Nordkapp Basin experienced halokinesis predominantly during the Early to Middle Triassic. However, the Nordkapp Basin cannot be considered as one large basin entity in relation to the timing of the salt movement, as there is observed differences in the two sub-basins. Hence, the Northeast sub-basin of the Nordkapp Basin is dominated by mainly Middle Triassic diapiric growth, and the southwestern by Early Triassic diapiric growth.

The size of the Nordkapp Basin is huge compared to the Tiddlybanken Basin. Moreover, the sub-basins of the Nordkapp Basin have different strike orientations compared to the Tiddlybanken Basin. The relationship between numbers of salt structures is incomparable, where the Nordkapp Basin has many and the Tiddlybanken Basin has few with a low salt budget. The Nordkapp Basin consists of mainly salt diapirs, walls and pillows, which are also observed in the Tiddlybanken Basin. As the Nordkapp Basin appear to have a greater amount of salt diapirs, the complexity of the timing of salt movement is greater. The diapirs have diachronous diapiric growth, creating available accommodation space spatially and laterally within the basin.

It is observed Triassic faulting along the basin margin hinge in the Nordkapp Basin, as a consequence of salt withdrawl, generating rim-synclines and steepening topography. However, this is not observed in the Tiddlybanken Basin. Additionally, faults have displaced the basement of the Nordkapp Basin and these are not identified in the Tiddlybanken Basin.

7.0 Facies, architecture and infill-style

7.1 Seismic package description and interpretation (L. Ladinian – M. Norian)

The seismic package analysis demonstrates seismic facies with thickness estimations in combination with amplitude extracts identified within the Snadd Formation in the Barents Sea Southeast (figures 20-23). These contribute to form the basis for interpretation of depositional elements and GDE (Gross Depositional Environments) within the Snadd Formation in the study areas. The identified stratigraphic sequences discussed in section *5.2 Stratigraphic framework and well correlation* are used in this section. The interval is further divided based on the regressive to transgressive cycles within the sequences ("Lower part" and "Upper part", respectfully).

To estimate the thickness of channelized bodies identified in the seismic data and in amplitude extractions (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*, data from wells nearby in the Barents Sea Southeast is used (Figure 20). These were used to estimate the channel thicknesses at every stratigraphic level at different depths.

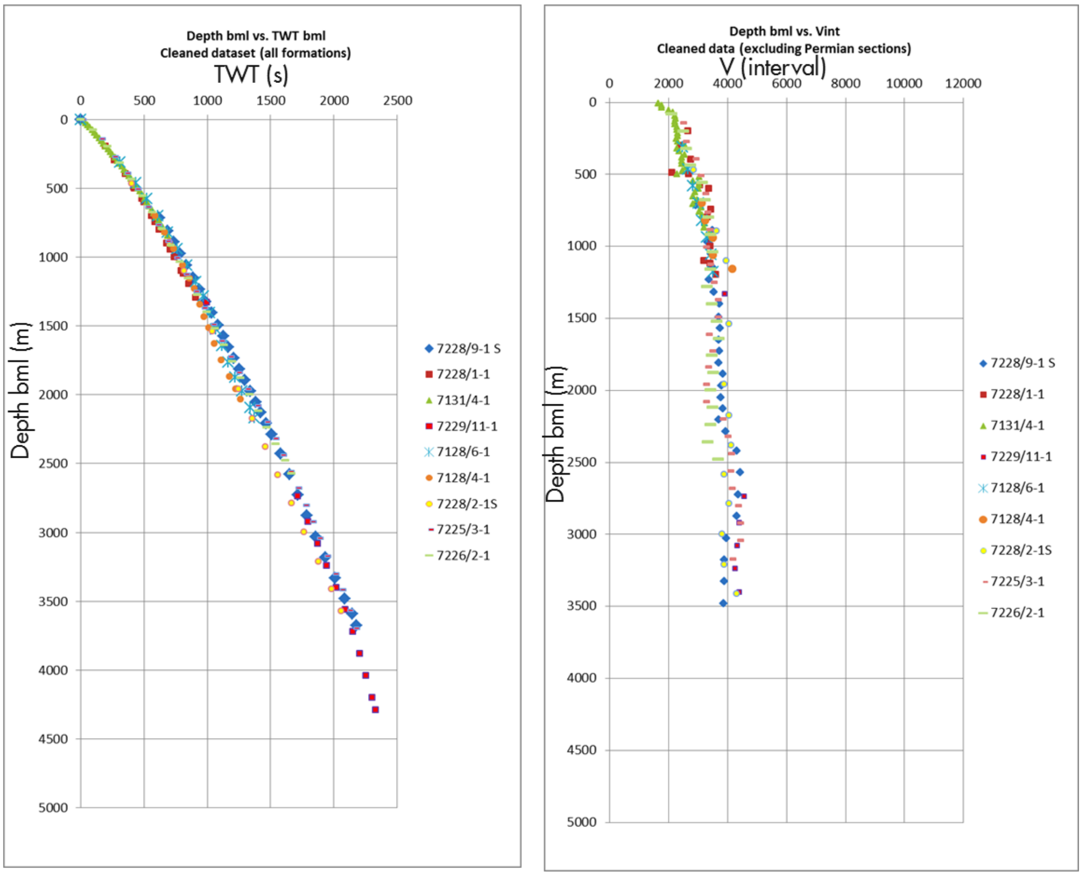
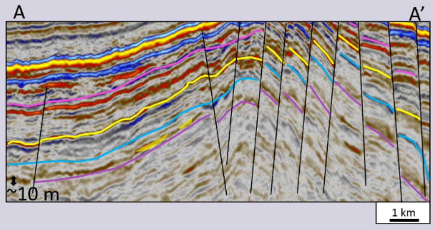
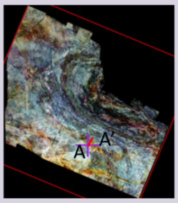
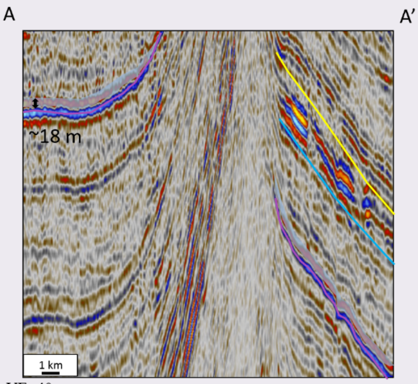
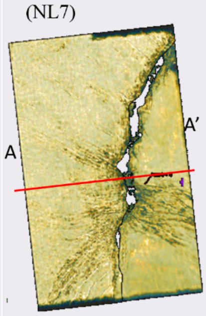
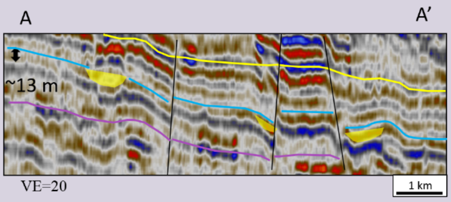
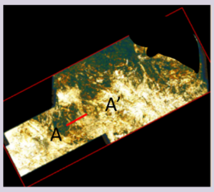


Figure 20: Velocity data from southeastern Barents Sea wells (provided in courtesy of Norske Shell).

Seismic package description and interpretation of Lower Snadd sequence (Ladinian)

Seismic Character	*Observation*	*Interpretation*	*Location*
 VE=10	Observations are based on the illustrated reflector of the lower part of the Ladinian package. The reflectors have relatively good continuity, with variable amplitude. Isolated, discontinuous and high amplitudes are identified and has a ribbon-like shape. These display to be relatively narrow and thin (around 10 meters thick).	**Lower delta plain** The muddy delta plain has an anastomosing fluvial system pattern on top of the Signalhorn Dome. These are estimated to be thin and narrow.	*Tiddlybanken Basin* *(TL8)* 
 VE=40	Observations are based on the illustrated reflector of the lowermost part of the Ladinian package. The reflector is continuous and has a high amplitude. It is conformable and has a thickness of approximately 18 meters.	**Shallow marine environment** Package above an maximum flooding event. There are no indications in the seismic data that there is any presence of a fluvial system, indicating a shallow marine environment (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*).	Nordkapp Basin (NL7) 
 VE=20	Observations are based on the illustrated reflector of the uppermost part of the Ladinian package. The reflectors are continuous and have variable amplitudes. There is identified ribbons-like features of discontinuous and high amplitude that are isolated. These are relatively narrow and thin (around 13 meters).	**Lower delta plain** It is interpreted to be located in the lower delta plain with thinner anastomosing channel systems distributing sandy to muddy material. The thin and narrow channels support the interpretation of the lower delta plain with associated anastomosing muddy system.	Finnmark Platform (FL5) 

Legend

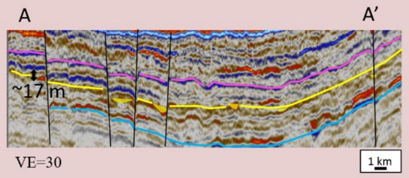
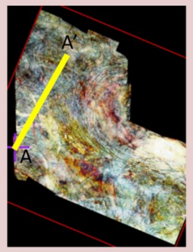
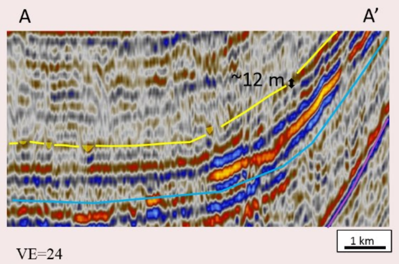
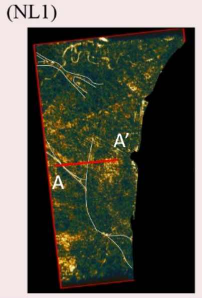
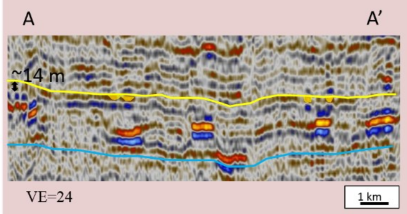
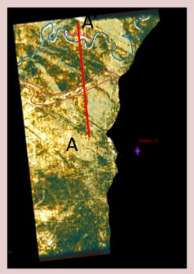
- Upper Snadd (U. Carn – M. Nor) top
- Lower Snadd (L. Carn) top
- Intra Lower Snadd (top Ladinian)
- Kobbe (Anisian) top
- Infill channel
- Stacked reflector
- Onlap

Hard Soft

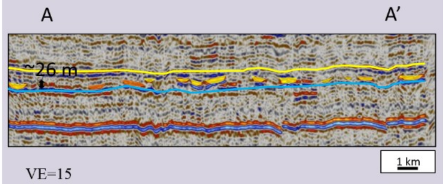
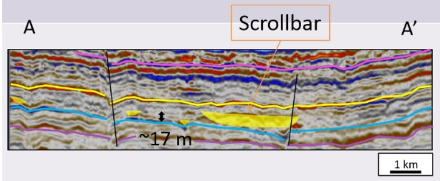
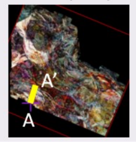
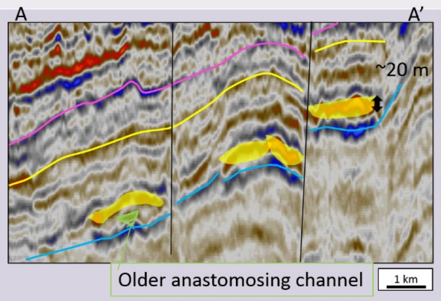
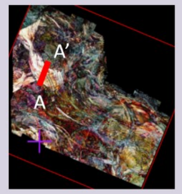
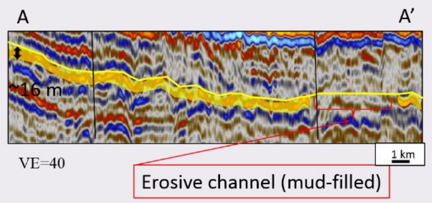
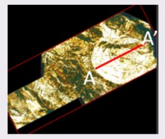
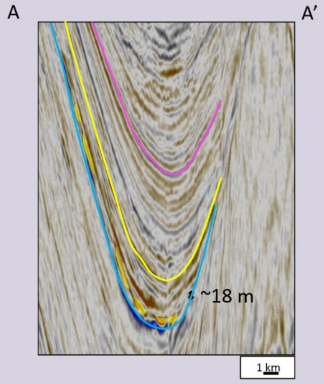
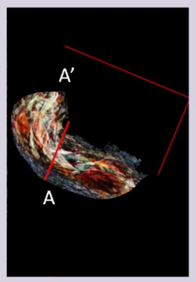
Figure 21: Seismic package description and interpretation of Lower Snadd sequence (Ladinian) with associated fluvial channel styles. It is interpreted as an overall progradational package (illustrated in the following sections).

Seismic package description and interpretation of Lower Snadd sequence (Lower Carnian)

Upper part

Seismic Character	*Observation*	*Interpretation*	*Location*
	Descriptions are made on the upper reflections in the upper part of the Lower Carnian package. Continuous and parallel reflectors with varying amplitude and frequency. Generally low to medium amplitudes. There are identified isolated, discontinuous high amplitude reflectors forming ribbon-like features. These ribbons have a thickness estimated to be 12 – 17 meters.	**Lower delta and coastal plain** The ribbons are interpreted as meandering to anastomosing channel infills. The depositional environment is muddy floodplain with meandering to anastomosing systems (further discussed in section *7.1 Attribute maps of Middle to Late Snadd (L. Ladinian – M. Norian)).* System is overall backstepping, and package is thinning landwards.	Tiddlybanken Basin (TL1) 
			Nordkapp Basin (NL1) 
			Nordkapp Basin (NL2) 

Lower part

Seismic Character	*Observation*	*Interpretation*	*Location*
	Observations are based on the illustrated reflector of the lower part of the Lower Carnian package. The layers are quite parallel, and amplitudes that are discontinuous and high forming isolated features. The thickness is estimated to be around 26 meters.	**Upper delta plain** Consists of channelized systems located on the upper delta plain. Older channelized bodies are identified in the seismic (orange color), with a more meandering character (supported by section *7.1 Attribute maps of Middle to Late Snadd (L. Ladinian – M. Norian*)). The fluvial channel fills are getting stacked and amalgamated on top of each other (discussed further in coming sections).	*Nordkapp Basin (NL3)* 
	Observations are based on the illustrated reflectors of the lower part of the Lower Carnian package. The reflectors are generally parallel, with variable amplitude and frequency. There are identified isolated, discontinuous amplitude reflectors forming different depositional features. Thickness of the features are ranging from approximately 16 – 20 meters.	**Upper deltaic plain** This interval has isolated channel- and channel belt fills. There is dominantly meandering responses associated with large meander belts. The features in the seismic is interpreted as deposits supporting a highly sinuos channel belt with scroll bar facies and point bar deposits with lateral accretion of (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian*)). As evident by the seismic data, younger channel systems incised through the channel systems present at the time of deposition. This is present on the Finnmark Platform and the Tiddlybanken Basin in the 3D seismic surveys. These are assumed to be mud-filled (TL 2 and FL2). The great thickness preserved of the system support a system experiencing late progradation (to aggradation).	Tiddlybanken Basin (TL2) 
			Tiddlybanken Basin *(TL2)* 
			Finnmark Platform *(FL2)* 
	Descriptions are based on the illustrated reflectors of the lower part of the Lower Carnian package in the Tiddlybanken Basin. The reflectors are parallel and continuous. Amplitude variations are observed, with high amplitudes and discontinuity of depositional features. Thickess of the features are estimated to be approximately 18 meters.	**Upper delta plain** Abundant channel fill in the base of the Lower Carnian package is interpreted. Increased accommodation space created in response to salt diapirism (see section *6.1 Structural evolution of the Tiddlybanken Basin*), and the rim-syncline is occupied with fluvial systems (further discussed in section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*).	*Tiddlybanken Basin (TL4)* 

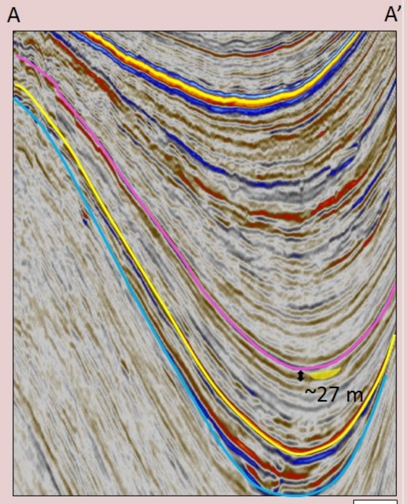
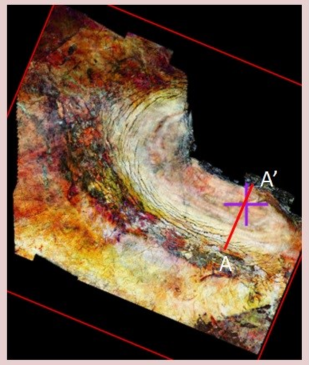
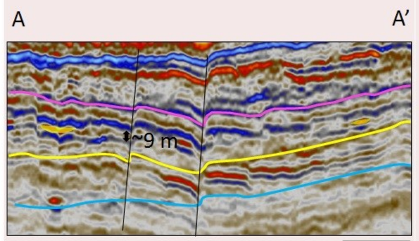
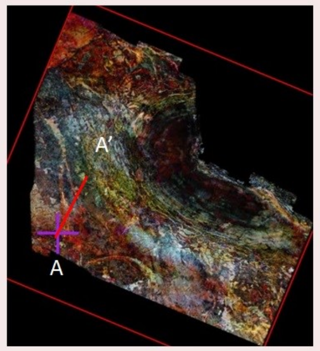
Legend

- Upper Snadd (U. Carn – M. Nor) top
- Lower Snadd (L. Carn) top
- Intra Lower Snadd (top Ladinian)
- Kobbe (Anisian) top
- Infill channel
- Stacked reflector
- Onlap

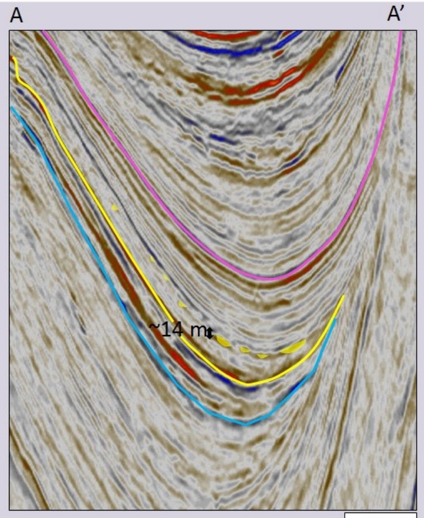
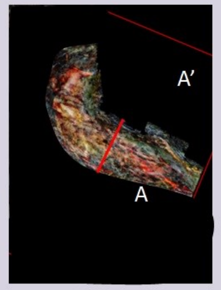
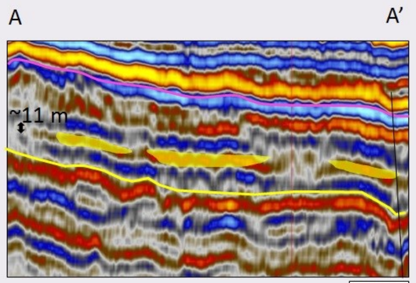
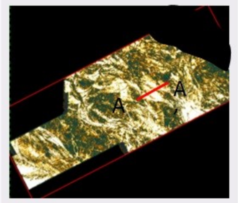
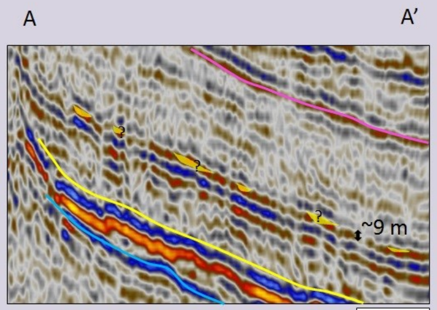
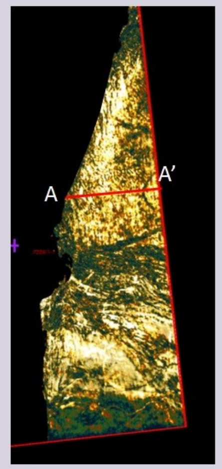
Hard Soft

Figure 22: Seismic package description and interpretation of Lower Snadd sequence (Lower Carnian) with associated fluvial channel styles. The «Lower part» is interpreted as progradational and the «Upper part» as retrogradational (these parts are recognized and illustrated in the following sections).

Upper part

Seismic Character	Observation	Interpretation	Location
 VE=16	Observations are based on the illustrated reflector of the upper part of the Upper Snadd sequence. The seismic reflectors are continuous and have relatively low amplitude and frequency. Some isolated, discontinuous high amplitude reflectors forming narrow ribbons are locally present. The thickness of the ribbons are estimated to be approximately 27 meters.	**Lower delta plain** There is identified a localized system coming into the basin, however quiet conditions with some fluvial activity are expected within the basin. This can be related to a lacustrine environment within the basin itself, left behind as the fluvial system retrogrades and moves landwards.	Tiddlybanken Basin (TU2) 
 VE=16	Observations are based on the illustrated reflector of the middle part of the Upper Snadd Formation. The seismic reflectors are sub-parallel to parallel, continuous to discontinuous with low to moderate amplitudes. Discontinuous, high amplitude reflectors forms narrow and thin ribbons-like features estimated to have a thickness of 9 meters.	**Lower delta plain** The western to northwestern part of the Tiddlybanken Basin has isolated channel style that split and rejoin. These are relatively isolated, thin and narrow. Together with the amplitude extraction data, it indicates anastomosing channels across the lower delta plain.	Tiddlybanken Basin (TU3) 

Lower part

Seismic Character	Observation	Interpretation	Location
 VE=15	Descriptions are based on the illustrated reflector in the lower part of the Upper Snadd sequence. The Late Snadd reflections in the Tiddlybanken Basin are continuous and have low to moderate amplitude and frequency. The package thickens in the basin, with identified higher amplitude reflectors that are discontinuous with a ribbon shape. The thickness of the observed ribbons is predicted to be 14 meters.	**Lower to upper delta plain** The ribbons are interpreted to be channels identified in the basin, and to onlap the Signalhorn Dome. Several channel fills are identified in the basin, associated with the creation of rim-synclines in response to salt growth (see section *6.1 Structural evolution of the Tiddlybanken Basin* and *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*).	*Tiddlybanken Basin (TU5)* 
 VE=20	Observations are based on the illustrated reflector in the middle of the Upper Snadd package. The seismic reflectors are relatively parallel and continuous. There is identified discontinuous, high amplitude reflectors formed as ribbons and narrow belts. The features have an assessed thickness of 11 meters.	**Upper deltaic plain** The interval is dominated by upper deltaic environment with the occurrence of several channel fills. These channels seems to be interconnected laterally (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*).	Finnmark Platform (FU4) 
 VE=15	Observations are based on the illustrated reflector of the middle part of the Upper Snadd sequence. The reflectors are even and parallel with moderate amplitude and frequency. Some isolated, discontinuous and high amplitude reflectors are forming isolated ribbons. The package is only present in the hanging wall. The reflector is estimated to be about 9 meters thickness.	**Upper to lower deltaic environment.** Seismic resolution is not good enough to distinguish clear evidence of distinctive channel bodies. However, fluvial systems are assumed to be present, but only within the Nordkapp Basin (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*). The seismic package is only present in the hanging wall due to the timing of fault activation caused by salt tectonic (see section *6.2 Structural evolution of the Nordkapp Basin*).	Nordkapp Basin (NU4) 

Legend

- Upper Snadd (U. Carn – M. Nor) top
- Lower Snadd (L. Carn) top
- Intra Lower Snadd (top Ladinian)
- Kobbe (Anisian) top
- Infill channel
- Stacked reflector
- Onlap

Hard — Soft

Figure 23: Seismic package description and interpretation of Upper Snadd sequence (Upper Carnian to Middle Norian) with associated fluvial channel styles. The «Lower part» is interpreted as progradational and the «Upper part» as retrogradational (these parts are recognized and illustrated in the following sections).

7.2 Attribute maps of Middle to Late Snadd (L. Ladinian – M. Norian)

Amplitude extraction is executed on every stratigraphic level of study areas 1, 2 and 3 (in figures 24-31). The evolution and fluvial styles of the Tiddlybanken and Nordkapp salt-mini basins are illustrated by a series of selected attribute maps (figures 24-29). Study areas 1 and 2 are the main focus areas, with the examples of salt (mini-)basins. Study area 3, the Finnmark Platform, (figures 30-31) is included for: i) comparison of the fluvial architecture between platform and salt-basin areas; and ii) to demonstrate the spatial variability in fluvial styles on the stable platform areas. Sediment supply rate maps (in true stratigraphic thickness) are created for the purpose of identifying the sediment supply rate per Ma. through the stratigraphic levels of the studies.

7.2.1 Tiddlybanken Basin attribute maps from the Middle to Late Snadd (Study area 1)

7.2.1.1 Tiddlybanken Basin attribute maps of Lower Snadd (L. Ladinian to U. Carnian) sequence

The Snadd Formation is divided into two main second-order genetic sequences, the Lower Snadd (L. Ladinian – U. Carnian) and Upper Snadd (U. Carn – M. Nor) mega-sequences (based on established framework in section *5.2 Stratigraphic framework and well correlation*).

<u>Ladinian prograding facies package</u>

Description

Amplitude maps are shown in Figure 24. At the base of the package (Figure 24, FK and TL8), lobate geometries are identified (maximum width ~20 km) with N-S oriented strong amplitudes. The remainder in the middle to upper part of the package appear relatively monotonous (Figure 24, TL7 and TL6). A ribbon-like body (about 1 km wide) with straight to low-sinuosity has a west-northwest to east-southeast trend. Secondly, there is identified an elongated ribbon like feature in the Tiddlybanken Basin with a west-northwest to east-southeast axis. The isopach map suggest a depositional thick depocenter in the eastern part of the Tiddlybanken Basin, close to the salt structures. Based on the isopach map the sediment supply preserved within the salt basin is up to 110 meters per Ma.

Interpretation

The lobate shapes present in the basal part is interpreted as delta lobes entering the area from south–southwest and south-southeast. The stronger amplitudes are accordingly interpreted to represent the distributary channel fills of the deltaic system (Figure 24, FK and TL8). The attribute maps in Ladinian age identifies a few narrow channels in the southwest and in the Tiddlybanken Basin (Figure 24, TL7 and TL6). These channels are interpreted to have an anastomosing pattern. These observed channels in the southwest and east, are following the same trend, but the entry point is different and therefor assumed to be sourced from another channel belt.

This stratigraphic package is interpreted to be overall prograding and is dominated by lower deltaic plain to coastal plain environment (as supported by section *5.2 Stratigraphic framework and well correlation* and *7.1 Seismic package description and interpretation (E. Ladinian – M. Norian*). This part of the Lower Snadd sequence is experiencing limited diapiric growth, in addition to no structural expression of the Signalhorn Dome that fits well with the interpretation (as discussed in section *6.1 Structural Evolution of the Tiddlybanken Basin*). The depocenter is close to the entry point of the Tiddlybanken Basin, also supporting this as a unit that seems to prograde and that the main flow system was located in the Tiddlybanken Basin.

<u>Lower Carnian facies package</u>

Description

The attribute maps from this package have huge variability in facies laterally and spatially (Figure 25). The lower part of the section has more amplitude variation compared to the upper part. Lower part (Figure 25, TL5) of the study can be split into different depositional features based on different identified characteristics. In Figure 25 (TL5), the southern area has narrow (~1 km wide) ribbon-like bodies that split trending towards northwest (sinuosity~1.1). There is an isolated and elongated shape in the Tiddlybanken Basin, dominated by multiple ribbon-like bodies that intersect and cross over one another (indicated in the Figure 25, TL5 (1)). In the middle part of the interval the internal architecture has a braided-like appearance (Figure 25, TL4 and TL3). The braided-like bodies are curved and sinuous (up to a sinuosity of 1.5) localized as a belt inside the Tiddlybanken Basin that has a northwestern trend (indicated in the Figure 25, TL5 (2)). In the northwest, a wide feature (about 8-9 km) displays a high degree of sinuosity (of ~1.7) that migrate with same orientation as the features above (indicated in the Figure 25, TL5 (3)). In the south-southwestern part, there is a highly sinuous ribbon/belt that is partly inside the 3D study area (Figure 25, TL 5 (4)). In the eastern part of this feature, there are narrow ribbon-like bodies in the outer bend that is not present in the western part. This western part shows internal architecture in the bend and within the study area it has a width of maximum 9-10 km (indicated in the Figure 25, TL5 (4)).

Towards the top of this package (close to the MFS), the features described above in the Tiddlybanken Basin and to the southwest are no longer identified (Figure 25, TL2). There are narrow ribbon-like shoestring geometry that range in width from 300 to 1000 meters. These split into several northwest to southeast oriented ribbon-like features (Figure 25, TL1). Two main depositional thick depocenters are identified along the salt wall and diapir inside the Tiddlybanken Basin. These depocenters has preserved 30-40 meters of sediments per Ma.

Interpretation

The attribute maps from this interval indicate variable style of fluvial architecture. Along the central part in a northwestern to southeastern strike the attribute extractions, the isolated ribbons are interpreted as anastomosing channels whereas meandering fluvial systems with lateral accretion are present further towards the northwest (indicated in the Figure 25, TL5 (1 And 3)). The meandering system has associated point bars (Figure 25, TL5 and TL 2 (3)). The localized and isolated system inside the Tiddlybanken Basin is oriented parallel to the salt wall (indicated in the Figure 25, TL5 (2), TL 4 and TL3). The Tiddlybanken Basin fluvial system consists of a large channel belt with multiple sinuous channels, creating a large channel complex. It is interpreted to be a combination of a bedload fluvial system to a mixed load system, defining a braided system with large meanders (Figure 25, TL5 (2)), which in turn suggests the presence of fluvial systems adjacent to the salt wall. Due to limited data access surrounding the diapir, it is not possible to map the extent of this system. However, it is assumed that the system is continuing downstream outside of the 3D seismic survey. The partly cut fluvial system towards the southwest is interpreted to be a part of a large meander belt with possible scroll bar feature (Figure 25, TL5 (4)). Attribute maps of the upper strata reveal a system that become more distal, with paleo-rivers that has eroded older strata in the Tiddlybanken Basin and to the southeast (Figure 25, TL2). In Figure 25 (TL1), the channelized system has pulled back and there are only visible distal distributary deltaic channels.

These fluvio-deltaic environments described above are quite different from the Ladinian age package in the Tiddlybanken Basin. From section *6.1 Structural evolution of the Tiddlybanken Basin*, salt in the middle of Tiddlybanken Basin started to withdrawl, and formed a salt-walled mini-basin in the rim-synclines adjacent to the salt diapir and wall as identified in the amplitude maps. This interval of the Tiddlybanken Basin has different controlling parameters, resulting in dissimilar facies, architecture and infill styles in the salt-walled mini-basin compared to the other systems in the south and southwest (laterally) and spatially. During E. Carnian, there is significant diapiric growth and the Signalhornet Dome is controlling the sediment distribution. The lower part of this package is interpreted to be a continuation of the progradation from Ladinian. The salt mini-basin is constrained by the salt wall and diapir in the Tiddlybanken Basin and by the uplifted Signalhorn Dome, creating a different meandering system from what is observed in the rest of the facies package. By the late stages of this interval, the anastomosing channels systems are interpreted to terminate against the Signalhorn Dome (Figure 25, TL1).

Throughout this interval, the system continues to prograde and extend the deltaic sequences as the sediment supply rate outruns the subsidence rate for most of the E. Carnian time. These systems are dominated by upper delta plain environments. Towards the end of the interval the system can no longer retrieve enough sediment supply and the system shift landward. As a result of this, the Tiddlybanken Basin is interpreted to be dominated by a lower delta plain environment with mixed load to suspended load fluvial systems by the end of the upper part of this interval.

The fluvial systems have the same entry points as Ladinian package. Two main depocenters are identified along the salt wall and diapir inside the Tiddlybanken Basin, based on the sedimentation rate map per Ma. Compared to the Ladinian depocenter, the depocenter has shifted basinward and is now located further into the basin towards northwest.

7.2.1.2 Tiddlybanken Basin attribute maps of Upper Snadd (U. Carn to M. Nor) sequence

Description

Amplitude maps are shown in Figure 26. Attribute maps from this sequence show a variation in geometry patterns of depositional elements throughout the sequence. The lower part of this sequence is only preserved within the Tiddlybanken Basin (Figure 26, TU6 – TU4) and has narrow (width of ~500 meters) and slightly curved ribbon features oriented northwest to southeast. In the middle of the sequence (Figure 26, TU3), it is identified elongated features on the south to northwest flanks of the survey area. These have an orientation of northwest and north-northwest and consist of relatively narrow ribbons (about 1.5 km wide) that anabranch and reconnect. Within the Tiddlybanken Basin, where there was previously ribbon-like geometries (Figure 26, TU6-TU4), that is now absent (Figure 26, TU3). In Figure 26 (TU3) the narrow ribbon shapes are oriented north-northwest towards the Tiddlybanken basin. However, the Tiddlybanken Basin has curved ribbon-like features with a southwest to northeast trend

(Figure 26, TU2). The top surface (Figure 26, TU1) has amplitude variations but show no specific/resolvable features.

The sediment supply map per Ma. indicate that the main depocenter was in the central part of the Tiddlybanken Basin. The thickness is here estimated to be up to 70-80 meters per Ma.

Interpretation

This is an interval consisting of fluvio-deltaic systems dominated distal fluvio-deltaic interaction. The paleo-rivers are transporting sediments with the same trends and orientation as in the Lower Snadd sequence. It is evident by the attribute maps that the channelized systems inside the Tiddlybanken Basin are constrained by the Signalhorn Dome and the uplifted salt wall (Figure 26 TU 6 – TU4). The Tiddlybanken Basin is a topographic low at this time, where narrow channels are feeding the localized mini basin as indicated by the thickness map (and established in section *6.2 Structural evolution of the Tiddlybanken Basin*). In the later stages of this sequence (Figure 26 TU3) the narrow depositional systems oriented north-northwest enters the Tiddlybanken Basin, and is interpreted to develop a lacustrine environment inside the Tiddlybanken Basin. Additional slightly curved channels from the southeast feed the mini-basin (Figure 26, TU2). The south and southwestern area is dominated by depositional features characterized as anastomosing channels that carry suspended load, showing evidence of avulsion. These fluvial systems are avoiding the Signalhorn Dome, and begin to turn once the system is closing in on the controlling high (Figure 26, TU6). The upper part of the sequence (Figure 26, TU1) is dominated by distal deltaic to marine environment.

The lower part of the sequence is characterized as a progradational unit, however the system is interpreted to shift landward due to a regional transgression in the upper part and generating a MFS recognized as Top Snadd Formation (more details about cycles of transgression and regression in the nearby wells are found in section *5.1 Stratigraphic framework and well correlation*). The system is prograding from the lower part of the interval, and starts to retrograde in the middle to upper part of the interval. It interpreted as an upper to lower delta plain depositional environment, however as the system continues to backstep, the fluvial systems move landward and the area is occupied by a marine environment.

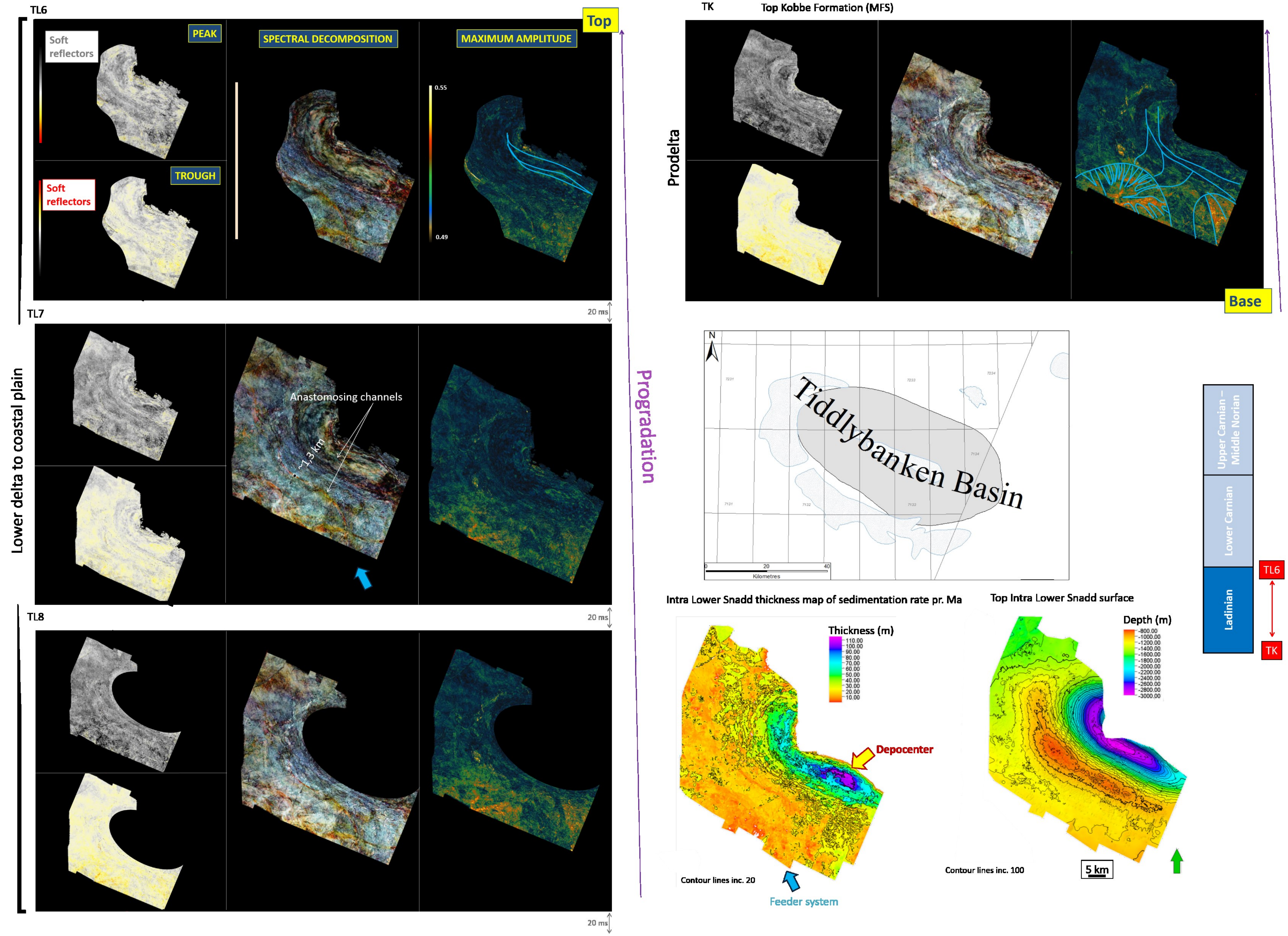


Figure 24: Attribute maps of the lower part of the Lower Snadd mega-sequence in the Tiddlybanken Basin.

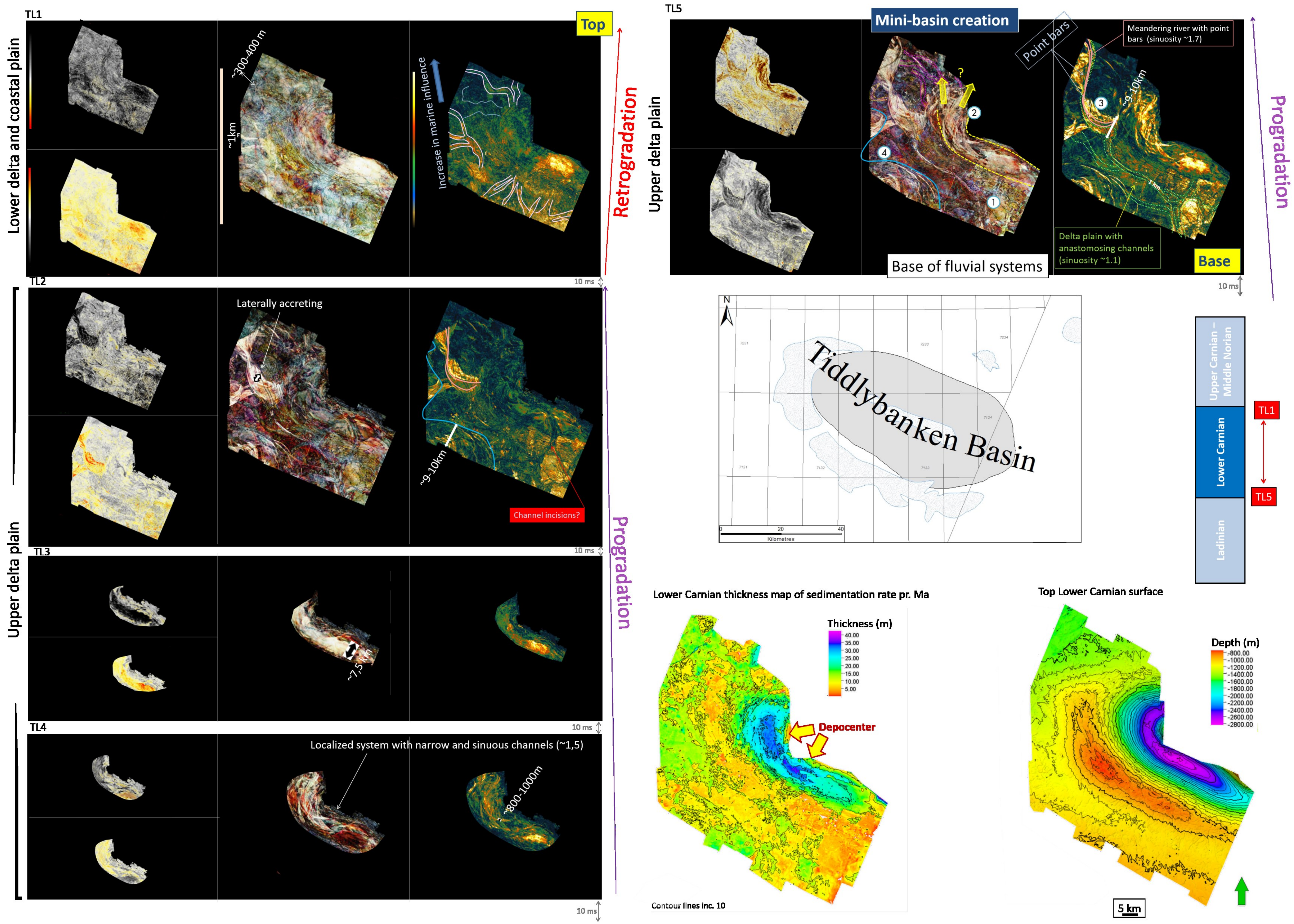


Figure 25: Attribute maps of the upper part of the Lower Snadd mega-sequence in the Tiddlybanken Basin.

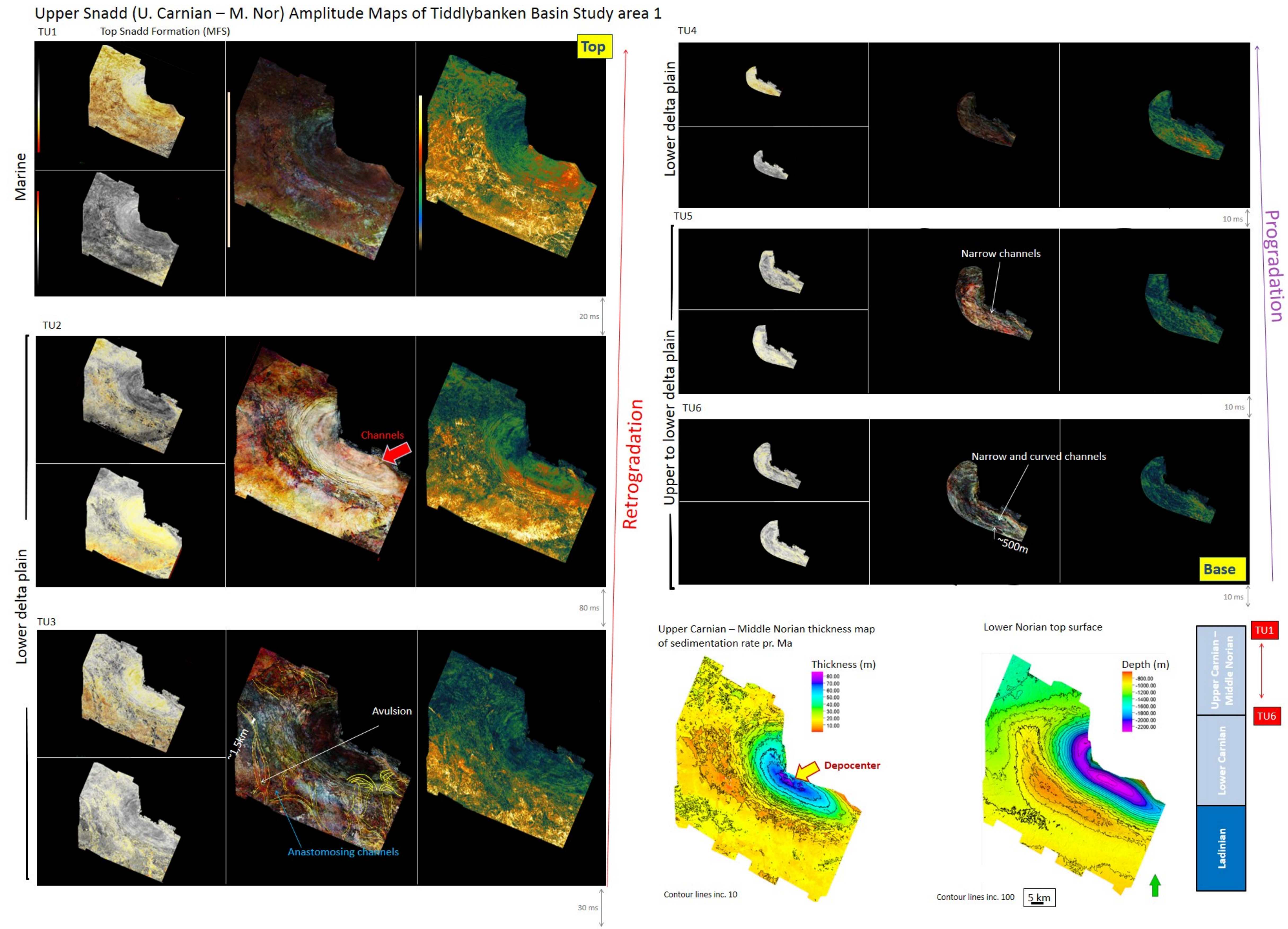


Figure 26: Attribute maps of the Upper Snadd mega-sequence in the Tiddlybanken Basin.

7.2.2 Nordkapp Basin attribute maps from E. Ladinian to M. Norian (Study area 2)

7.2.2.1 Nordkapp Basin attribute maps of Lower Snadd (L. Ladinian to U. Carnian) sequence

The Snadd Formation is divided into two main second-order genetic sequences, the Lower Snadd (L. Ladinian – U. Carnian) and Upper Snadd (U. Carn – M. Nor) mega-sequences (based on established framework (see section *5.2 Stratigraphic framework and well correlation*).

Ladinian prograding facies package (Study area 2)

Description

The attribute maps from the Ladinian package show increase in amplitude variations from base to top of interval (Figure 27). No lateral amplitude variations are captured in the deeper packages (Figure 27, NK and NL7). In the upper part, distinctive ribbon-like features are identified that has an increase in sinuosity and width in the younger stratigraphic intervals (Figure 27, NL6 to NL5). In Figure 27 (NL6) there are narrow (width ~500 meters) and relatively straight high amplitude ribbons that split with an orientation of northwest to southeast. These narrow straight ribbons are not captured by the nearby wells, though narrower features might not be resolvable and therefore can be captured by the wellbore (not possible to identify based on the maps) (Figure 27, NL6). The attribute map from the top interval (Figure 27, NL5) has less narrow (about 500 to 1000 meters wide) ribbon-like bodies. These narrow features are moderately sinuous (ranging from to 1.25 to 1.35). Wider features are identified on the Bjarmeland Platform with a sinuosity slightly above 1 that is splitting and reconnecting. These have the same orientation trend as previous features in the package. There is additionally identified very narrow ribbons that are highly sinuous (~1.7), in the northwestern area, with a different orientation present at the Bjarmeland Platform.

The main depositional thick depocenters are located in the northeast and southeast area within the Nordkapp Basin.

Interpretation

This interval is recognized by its increase fluvio-deltaic activity. Top Kobbe Formation is picked as a marine maximum flooding surface (Figure 27, NK), and display no lateral amplitude changes representing the top Steinkobbe Formation (MFS). The younger stratigraphic reflector in Figure 27 (NL7) display similar behavior and is interpreted to be in a marine to shallow marine environment. It is interpreted that the channelized systems identified in the upper part of the interval is filling the hanging wall and starts to transport sediments out of Study area 2

(Figure 27, NL6 and NL5). The anastomosing pattern in the upper part (Figure 27, NL6) is believed to be on the distal delta plain, and in the uppermost part (in Figure 27, NL5) the study area is dominated by a different system that has anastomosing to meandering characters.

Marine to shallow marine depositional environment is dominating the lower part of the package. The extent of the deltaic systems starts to move basinward and the study area is located more landward as the systems continue to prograde. It is interpreted to change from a delta front with narrow distributary channels to lower delta plain environment (Figure 27). The channel systems in this interval are interpreted to overall prograde into the Nordkapp Basin (and Study area 2) and mainly exit on the flank of Study area 2. There is identified channels on the Bjarmeland Platform in Figure 27 (NL5) with another orientation (in the north) that is interpreted to be sourced from an alternative channelized belt that is not present inside the Nordkapp Basin. This interval is interpreted as a progradational package that continue to prograde into Late Carnian to Middle Norian sequence (further described in section *5.2 Stratigraphic framework and well correlation*).

The point of entry for the high amplitude pattern and depocenters indicate that the features are mainly sourced from the northeast and southeast, and passes over the basin margin hinge and onto the Bjarmeland Platform (Figure 27). The timing of sedimentation seems not to be controlled by salt piercement (see section *6.2 Structural evolution of the Nordkapp Basin*).

E. Carnian facies package

Description

Amplitude maps are shown in Figure 28 and the package reveals heterogeneous amplitude variations that are observed to have different orientations. In the lower part of the package (Figure 28, NL4 and NL3) it is identified several ribbon-like features and belts with a great amplitude, that follow a specific pattern through Study area 2. Elongated features are identified in the maximum amplitude maps on the Bjarmeland Platform oriented south to north and northeast to southwest (Figure 28, NL4 indicated with arrow M). The western feature has a width of approximately 200 meters with associated depositional geometries that laterally migrate (sinuosity ~1.5) and the eastern features has a width of approximately 800 meters. In Figure 28 (NL3 indicated with arrow C1) there is identified a belt that is highly sinuous in shape (sinuosity ~1.75), located in the study area from the northeast towards northwest. This belt is 4-5 km wide and is partly splitting on the Bjarmeland Platform. Within the same figure, another feature is identified in the northern part of the Bjarmeland Platform. It is oriented northwest to southeast (Figure 28, NL3 indicated with arrow B1). This is a belt with some higher amplitudes, with a braided-like appearance with the same directional trends with low sinuosity and a maximum width of 10 km. An additional feature is identified in the southeastern part of the Nordkapp Basin, with a northwest to southeast orientation (Figure 28, NL3 indicated with arrow C2). This follows a trend of soft amplitudes, that it is quite chaotic, and therefore not possible to distinguish geometries in this area. In the upper part of the package it is identified narrower ribbon-like bodies (Figure 28, NL2 and NL1 indicated with arrow M2 and A). Due to software challenges and rapid facies changes in the seismic data, it has not been possible to extract information about these stratigraphic intervals inside the margin of the Nordkapp Basin. The identified ribbons in Figure 28, NL2 show two main ribbon-like bodies, located in the northern part of the study area. The northernmost feature is highly sinuous (sinuosity ~2) and narrow (~100–200 meters) and has a southwest to northeast orientation. The adjacent ribbon is wider, less sinuous (sinousity~1.3) with similar orientation. The uppermost attribute map has narrow ribbon-like high amplitudes oriented towards northwest (Figure 28, NL1 indicated with arrow A). These shapes have a width about 200 meters and splits towards the northwest to southeast and are slightly sinuous (sinuosity ~1.1), but dominantly straight.

The sediment supply rate isopach map indicates that the major depositional thick depocenter is located within the Nordkapp Basin to the southeast. It has a thickness up to 40 meters per Ma., in addition to a minor depocenter in the northeast (with thickness up to 25-30 meters per Ma.).

Interpretation

The attribute maps reveal the presence of different fluvio-deltaic styles (Figure 28). The interpreted orientation of the systems is indicated in Figure 28 with different arrows. In Figure 28 (NL4) the amplitude pattern is interpreted as a meandering system outlined with a trend towards the southwest (Figure 28, NL4 arrow M). Associated depositional features are point bars with laterally accretion of approximately 800 meters downstream. Additional amplitude belts are identified as fluvial systems, and these are bypassing and moving in slightly different directions through this time interval (as demonstrated by the indicated arrows at the extractions and thickness map in Figure 28 (NL3)). Several fluvial systems are identified in the lower part of this package, including a highly sinuous meander belt as illustrated in Figure 28 (NL3 arrow C1). It is believed to be a multistorey channel complex that slightly curves from a northeast direction until it goes over the basin margin and split into several channels to the west on the Bjarmeland Platform. From the well correlation, wellbore 7228/2-1 S within the basin has a more amalgamated sandstone bodies compared with the 7228/1-1 well (see section *5.2 Stratigraphic framework and well correlation)*. The northwestern channel belt with a width of 10 km is identified in the north to northwestern part of the attribute map, is interpreted to have braided signature with multiple channels (Figure 28, NL3 indicated with B1 arrow). In the upper part of the package, narrow and highly sinuous channel-fills are interpreted as a meandering fluvial system. It is migrating from northeast to west on the Bjameland Platform. There are identified a high amplitude pattern between the meander loops, believed to have been generated as the meander neck is cut off (Figure 28, NL3). The uppermost part of the package is characterized by its anastomosing behavior and avulsion (Figure 28, NL1 arrow A).

The sediment supply rate isopach map indicates that most of the sediments are coming from the central part of the Nordkapp Basin, with two localized depocenters in the northeast and southeast. The lower part of the interval is interpreted to gradually prograde, and as a result the period is dominated by high abundancy of fluvial systems in the upper delta plain. The upper part of the package is interpreted to overall retrograde into a coastal plain environment. As the deltaic systems move landward (Figure 28, NL), narrow meandering to narrow anastomosing paleo-channels occupies the area due to the retrogradation. There are some channelized systems that is interpreted to have a different source from the north to northeast (Figure 28, NL3 (arrow M) and NL2 (arrow M2).

The upper Lower Snadd package in Study area 2 of the Nordkapp Basin, has been interpreted to not have any significant salt movement (see section *6.2 Structural evolution of the Nordkapp Basin*). The fluvio-deltaic environment is as a result, prograding and bypassing the Nordkapp Basin, as the presence of accommodation space rate is less than sediment supply rate during progradation.

7.2.2.2 Nordkapp Basin attribute maps of attribute maps of the Upper Snadd (U. Carn – M. Nor) sequence

Description

Amplitude maps are shown in Figure 29. The lower part of the sequence has a unit that is only present in the hanging wall (Nordkapp Basin), which is absent on the footwall (Bjarmeland Platform). It has variable amplitudes and the majority of soft events based on the trough attribute map indicate that these are located in the northwest (which is the depocenter identified in the isopach map) (Figure 29, NU4 arrow C). In Figure 29 (NU3 arrow M), depositional features with high amplitudes that are highly sinuous and cross over each other are identified with a southeast with a southwest to northeast trend. These are relatively narrow (width of ~100-300 meters) and is occupying the space where the main depocenter of the sequence is located. Additionally, it is identified some partly sporadic amplitudes on the flank of the Nordkapp Basin (resolution limitation?). Attribute maps from the upper part (Figure 29, NU 2 and NU1) have are amplitude variations, though it is not possible to distinguish any specific amplitude patterns. There is identified some ribbons in the study area, that are relatively straight to sinuous with a width of approximate 800 meters (Figure 29, NU2). In the Top Snadd Formation (MFS), there are some lateral amplitude variations but no features are identified (Figure 29 NU1).

Interpretation

In this section it is interpreted to consist of channelized systems, dominantly in the lower part of the package. The lower part of the sequence is dominantly located within the two main depocenters (Figure 29, NU4 and NU3). It is interpreted a channelized system feeding the area from the northeast within the Nordkapp Basin, and another system with narrow channels with meandering character entering the study area in southeast and migrate northwest (Figure 29, NU4 and NU3).

During L. Carnian – M. Norian time there was salt diapirism and activation of the boundary fault zone between the Nordkapp and Bjarmeland Platform. As a result, accommodation space was generated in the Nordkapp Basin within the hanging wall (see section *6.2 Structural evolution of the Nordkapp Basin*). As a consequence, the fluvial channels migrated to this topographic low, and therefore more abundant channel-fills are identified inside the Nordkapp Basin (Figure 29, NU3). Once the subsided area was filled up, the fluvio-deltaic systems continued to prograde and migrate over the basin margin. Based on the thickness map and lack of any geomorphical elements in the upper part of the sequence, is interpreted to be located relatively distal on the coastal plain (Figure 29, NU2). The retrogradational part change from a meandering to anastomosing character, and eventually into a marine setting supporting the interpretation of Top Snadd Formation as a MFS.

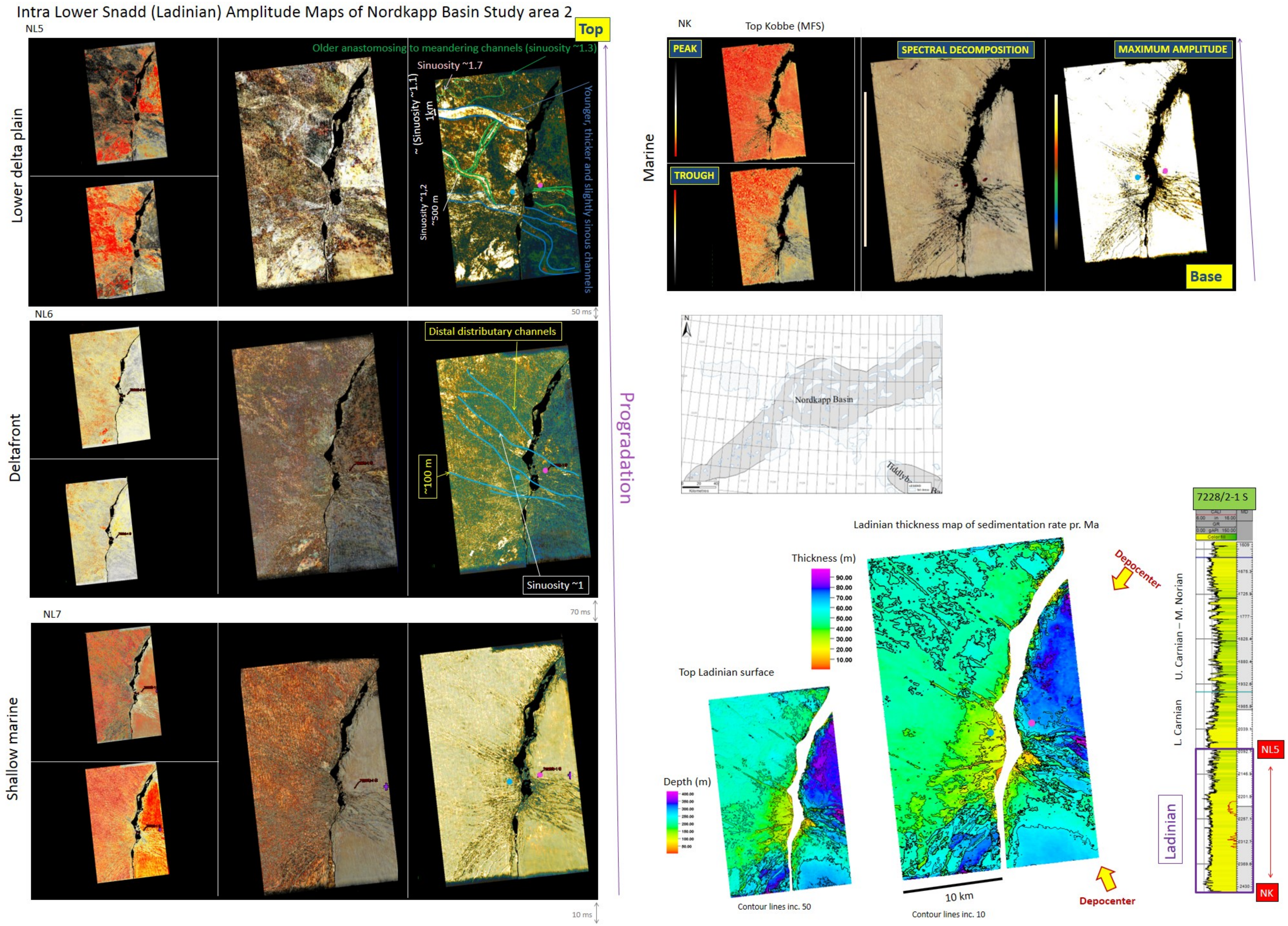


Figure 27: Attribute maps of the lower part of the Lower Snadd mega-sequence in Study area 2 in the Nordkapp Basin.

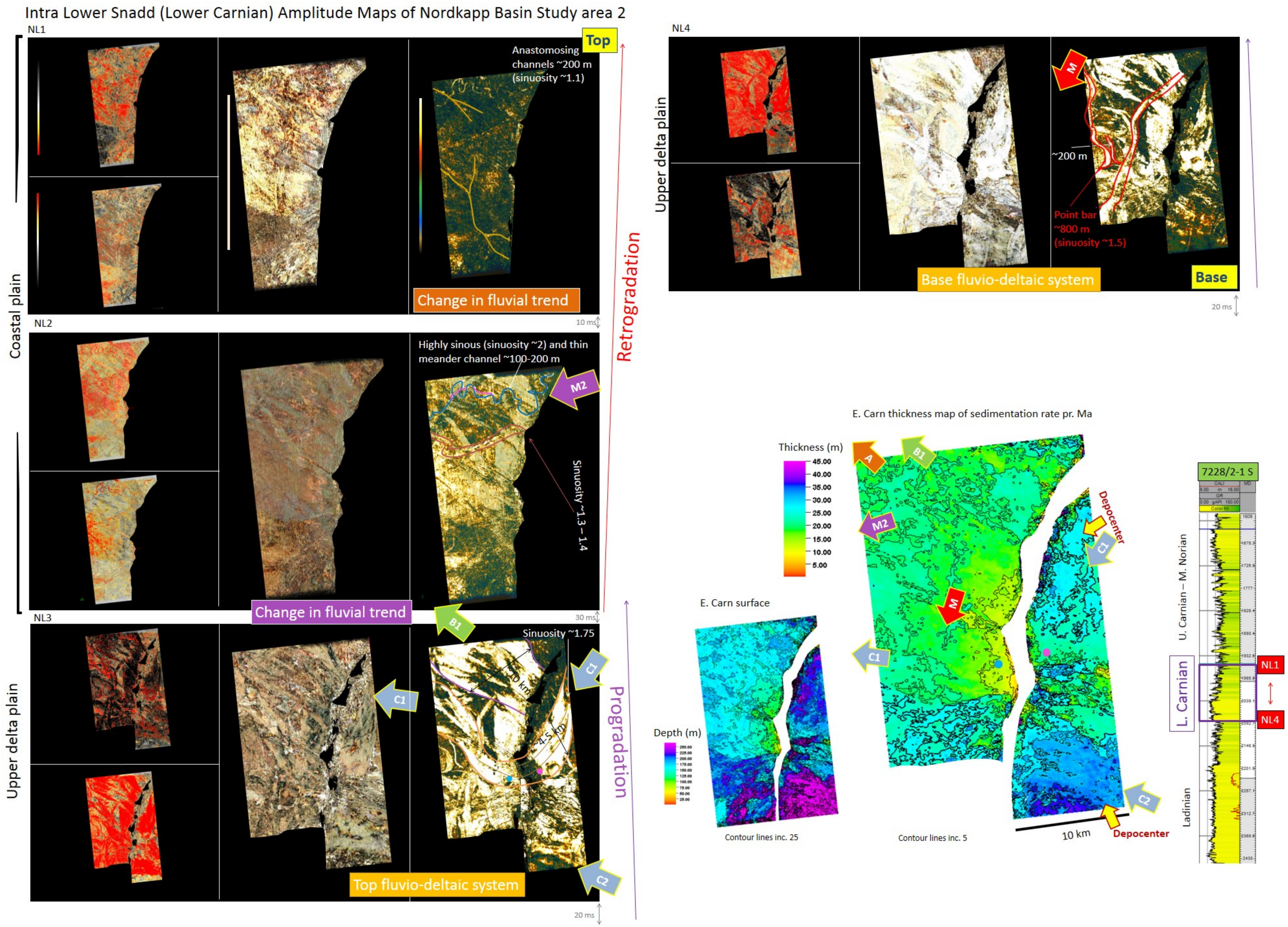


Figure 28: Attribute maps of the upper part of the Lower Snadd mega-sequence in Study area 2 in the Nordkapp Basin.

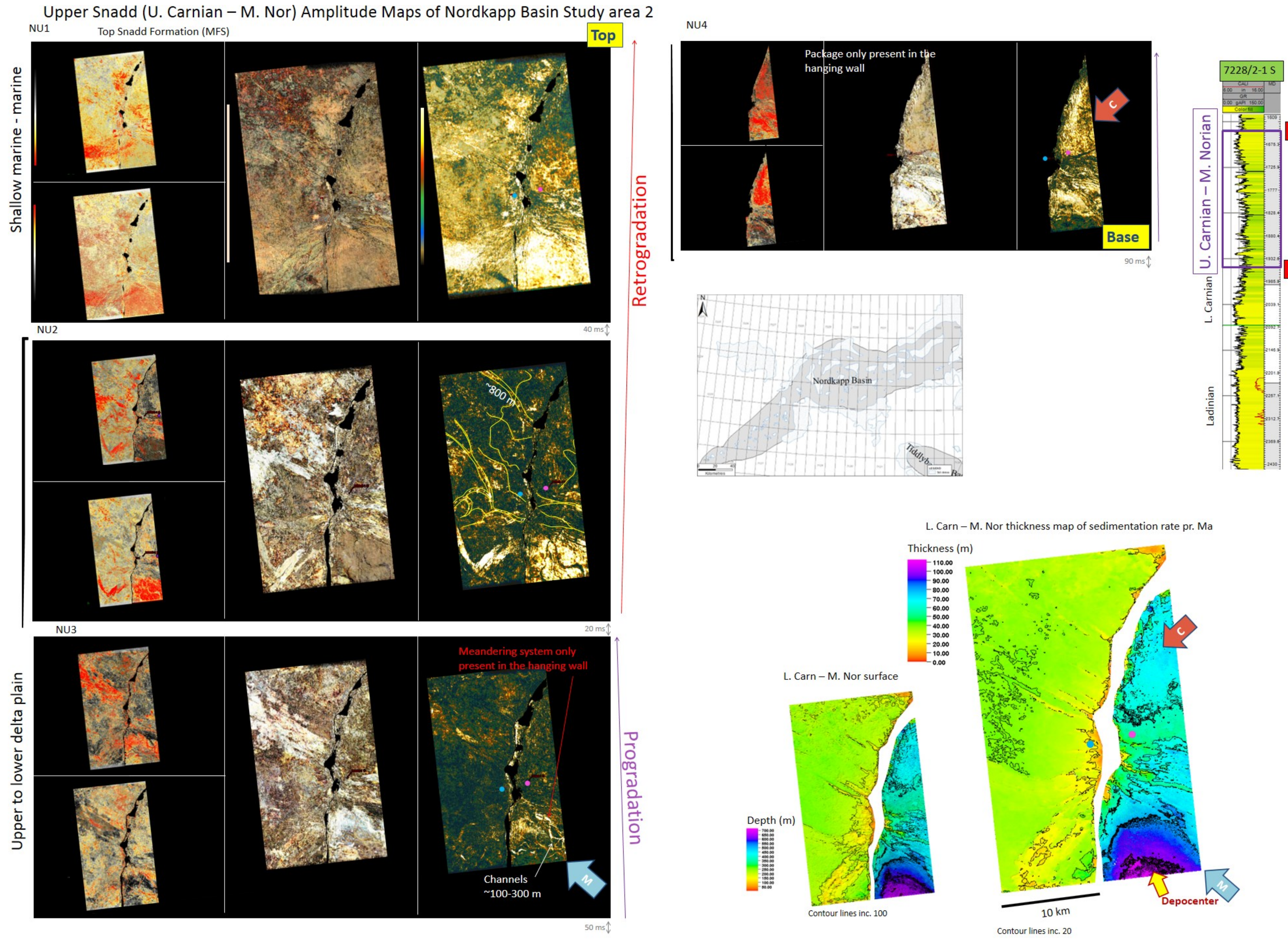


Figure 29: Attribute maps of the Upper Snadd mega-sequence in Study area 2 in the Nordkapp Basin.

7.2.3 Finnmark Platform attribute maps from E. Ladinian to M. Norian from the (Study area 3)

The Snadd Formation is divided into two main second-order genetic sequences, the Lower Snadd (L. Ladinian – U. Carnian) and Upper Snadd (U. Carn – M. Nor) mega-sequences (based on established framework (see section *5.2 Stratigraphic framework and well correlation*).

7.2.3.1 Finnmark Platform attribute maps of Lower Snadd (L. Ladinian and U. Carnian) sequence

Description

Amplitude maps are shown in Figure 30. The lower part of this sequence is dominated by high to moderate sinuosity ribbon-like bodies that migrate through the study area. These are narrow (width ~500 meters) in the lowermost part (Figure 30, FK) and develop into wider ribbons with more amplitude changes laterally (Figure 30, FL4). In the middle part of the sequence (Figure 30, FL3 to FL2) the attribute maps have a half-circular shaped feature that indicates a highly sinuous feature with high amplitudes and some internal architecture. Within the survey, it has a total width of approximately 23 km and covers the entire eastern Study area 3. There is evidence of an additional feature in the same area, oriented towards west-northwest with a different geomorphic character. The western part has a ~10 km wide belt that is relatively straight in shape and oriented towards the northwest. Upper part of the sequence, display a variety of ribbon-like features (width about 2.5 km) and limited degree of sinuosity. There is also observed narrower ribbons that are highly sinuous (width ~100 meters) in addition to features that are relatively straight, anabranch and reconnect (approximate range of width is 300-500 meters). The highly sinuous feature with a quite narrow shape is dominantly found in the western part of the study area (Figure 30, FL1).

Interpretation

This package is interpreted to be affected by fluvio-deltaic systems, with changing geomorphology down-stream. In the lower part of the package, the channel infill is interpreted to belong to a paleo-anastomosing to slightly meandering river system (Figure 30, FK to FL4). In the middle part of the sequence (Figure 30, FL3 and FL2) it is two main channel complexes are identified. The laterally accreting feature is interpreted as a large scroll bar, a part of a meander belt. Beneath it there is interpreted a different channelized system that has a slightly different orientation, architecture and shape. The scroll bar has a lateral accretion to the southwest migration toward the north (in the direction of the Nordkapp Basin). The second feature is located in the western area, and shows little architecture or indications of fluvial style

(Figure 30, FL2). In the same figure there is evidence of a younger channel system in the eastern part of the survey, eroding down into the large scroll, that is mud-filled (also supported by *7.1 Seismic package description and interpretation (E. Ladinian – M. Norian*). In Figure 30 (FL1), meandering fluvial systems develop into more anastomosing systems with avulsion pattern.

The lower part of the sequence is interpreted as a progradational unit. As the deltaic environment extends further into the basin lower deltaic plain is overlayed by upper delta plain with large meander belts with associated scroll bars. Towards the upper part of the sequence, the system starts to retrograde going from wide sinuous channels (about 2.5 km) to narrow meandering to anastomosing infill-channels (width about 500-100 m).

The attribute maps have a variety of fluvial channels systems that is able to flow relatively undisturbed as there is not any interference with salt diapirism or topographic elements restricting the extent of the channels. Throughout this interval, it is a system mainly prograding with a short period of retrogradation (also indicated by the well correlation in section *5.2 Stratigraphic Framework and well correlation*).

7.2.3.2 Finnmark Platform attribute maps of Upper Snadd (U. Carn – M. Nor) sequence

Description

Amplitude maps are shown in Figure 31. The attribute maps from this interval display amplitude variation in the lower part of the sequence that become more homogeneous in the upper part (Figure 31, FU4-FU1). There is interconnected, sinuous, anabranching and belts with straight features in the lower part of the sequence (Figure 31, FU4 and FU3). Wider amplitude belts (~3-4 km) have a range of 1 to 1.1 in sinuosity, and the narrow (300 meters) has with a sinuosity about 1.5 in the same maps (Figure 31, FU4 and FU3). The upper part of the sequence is dominated by narrow ribbons in the central to western part of the survey that disappear eastward (Figure 31, FU). The uppermost map of the MFS (Figure 31, FU1) has some bands of amplitude variations, but no distinguishable features are observed. The overall depositional features become wider and more extensive from Figure 31 (FU4 to FU2).

Interpretation

The attribute maps show active fluvio-deltaic channel systems in the beginning to the middle of the interval, with decrease in abundancy of fluvial systems towards the top. The lower part is believed to (Figure 31, FU4 and FU3) have multiple channel complexes that are several times gets divided due to avulsion. The narrow ribbons are interpreted as anastomosing channel-infill, overlain by migrating younger infill channels with a width of 3 km. It is identified anastomosing channels in the upper part in the western area with less fluvio-deltaic activity to the east (Figure 31, FU2). The Top Snadd Formation (MFS) has some lateral variations, but no fluvio-deltaic activity is identified.

The lower part of the system is interpreted be in an upper to lower deltaic plain. As the system progrades, the younger fluvial sequences are stacked on top of the older and narrower channel bodies. The retrogradational depositional environment is dominated by a coastal to marine environment, where the fluvio-deltaic system is shifted landwards. Similarly, to the Lower Snadd sequence, is this sequence deposited on a stable platform structure. Mutual for the study area is the main entrance point for features are located in the south (southeast and southwest included) with an overall orientation towards the north to northwest. The main entrance point for the fluvial channel systems are located in the south (southeast and southwest included) with an overall orientation towards the north to northwest.

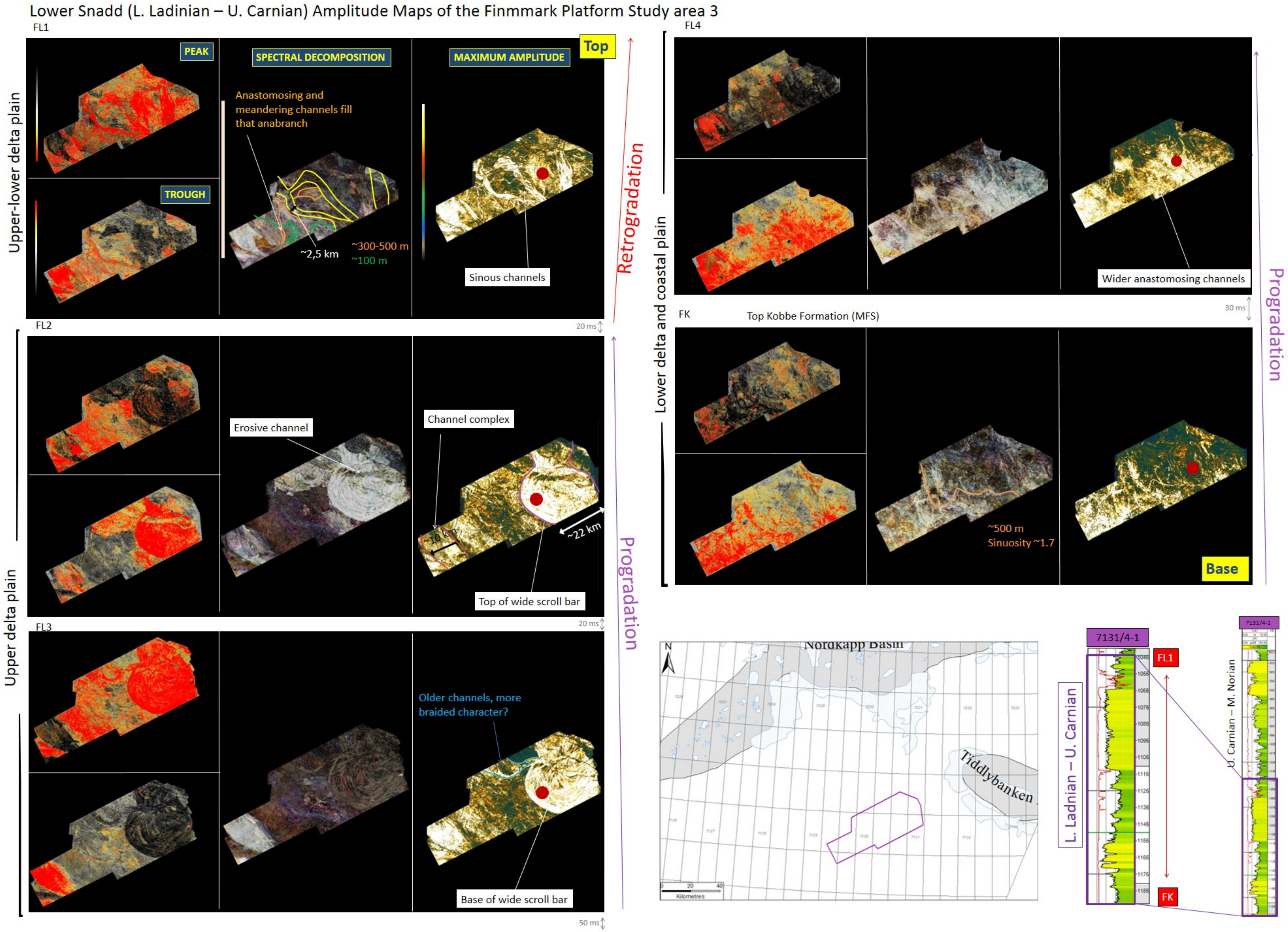


Figure 30: Attribute maps of the Lower Snadd mega-sequence in Study area 3 on the Finnmark Platform.

Upper Snadd (U. Carnian – M. Nor) Amplitude Maps of the Finnmark Platform of Study area 3

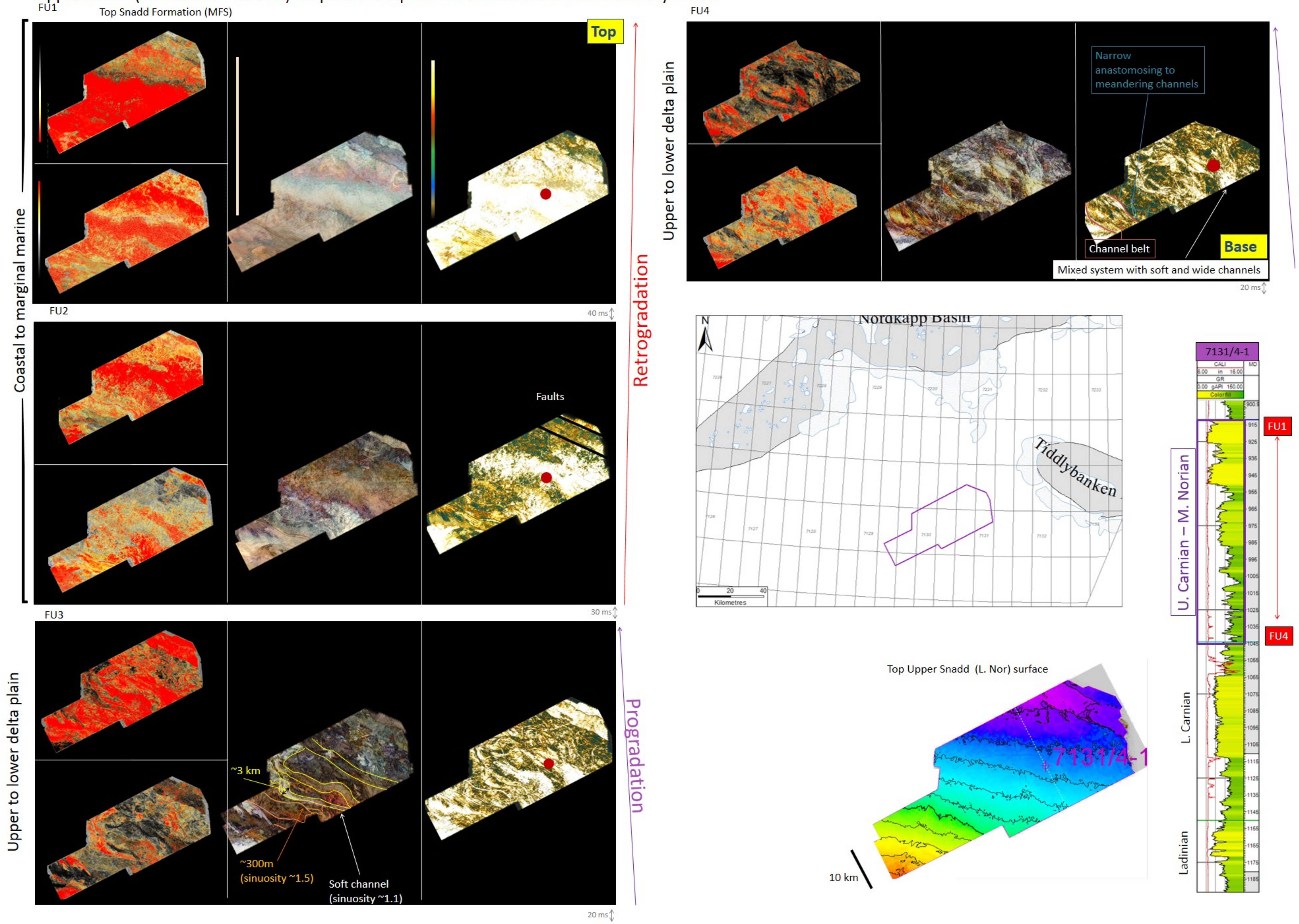


Figure 31: Attribute maps of the Upper Snadd mega-sequence in Study area 3 on the Finnmark Platform.

7.3 Core Inspection

The Snadd Formation is cored in the 7131/4-1 and 7228/7-1A wells. The cores are taken from the Lower and Upper Snadd sequences (figures 32 and 33).

7.3.1 7131/4-1 core

The 7131/4-1 cores were described by Klausen (2013) who interpreted the Snadd Formation to consist of a large sandy channel belt. The core sample from the Lower Snadd sequence was interpreted to consist of fining upwards sequences.

7.3.1.1 Lower Snadd sequence core (core 2)

Description

Three units were identified on the core, identified as unit 1, 2 and 3. Unit 1 is comprised of a coaly succession that is predominantly muddy. In the basal part of Unit 2, 1 meter thick conglomerate is present. There are thin conglomerate lags interbedded with the cross-stratified medium grained sand. In Unit 3, at approximately 1088-1095 meters, a succession of conglomerate overlain by a 10 meter cross-stratified and trough-stratified medium grained sandstones. At 1077-1070 meters, the medium grained sandstone is cross-stratified.

Interpretation

Unit 1 with the presence of coal in muddy material is classified as floodplain deposits. It is erosionally overlain by channel conglomerates forming a channel base lag in Unit 2. A second channel base lag of conglomerate is identified above an erosional surface in Unit 3, at around 1094 meters. This channel has similarities with the remains of channel story fills, dominated by aggradational sets of cross- to trough-stratified sandstones. These are interpreted to represent bars of braided rivers. Only the upper part of Unit 3 has a motif more typical of meandering fluvial systems (fining upwards trend). This contradicts the findings in the attribute maps (Figure 30), which suggest a meandering fluvial system (as suggested by Klausen (2013)), and is best resolved with a hybrid braided to meandering fluvial system (or braided system with a meander channel course) (see section *7.2.3 Finnmark Platform attribute maps from E. Ladinian to M. Norian from the (Study area 3)).*

7.3.1.2 Upper Snadd sequence core (core 1)

Description

Two units were identified on the core, named unit A and B. At the base of unit A, there is a thin conglomerate succession. It is overlain by an 8 meter thick trough-stratified fine to medium-grained sand. In the upper part of the unit, there is fine to very fine-grained sandstone that is partly interbedded with claystones and siltstones and there is evidence of bioturbation. In unit B, at approximately 915-925 meters, a conglomerate layer of about 0.5 meters is identified at the base. The overlaying interval consist of sandstone with horizontal- to low angle-stratification. From 915-918 meters there is a decrease in grain size to fine-grained sand, in addition to weak to moderate bioturbation.

Interpretation

The lower part of unit A has a fining upwards response. In the GR-log and in the core, and is interpreted to represent a meandering fluvial system. Unit B is interpreted to have the same characteristics and also represent a meandering system. This corresponds well with the attribute maps (see section *7.2.3 Attribute extraction from the Finnmark Platform (Study area 3)*) and the predicted channel system proposed by Klausen (2014). Because conditions are expected to be more quiet, due to bioturbation being present in this part, the upper part of Unit A is interpreted to represent a bay and crevasse splay complex.

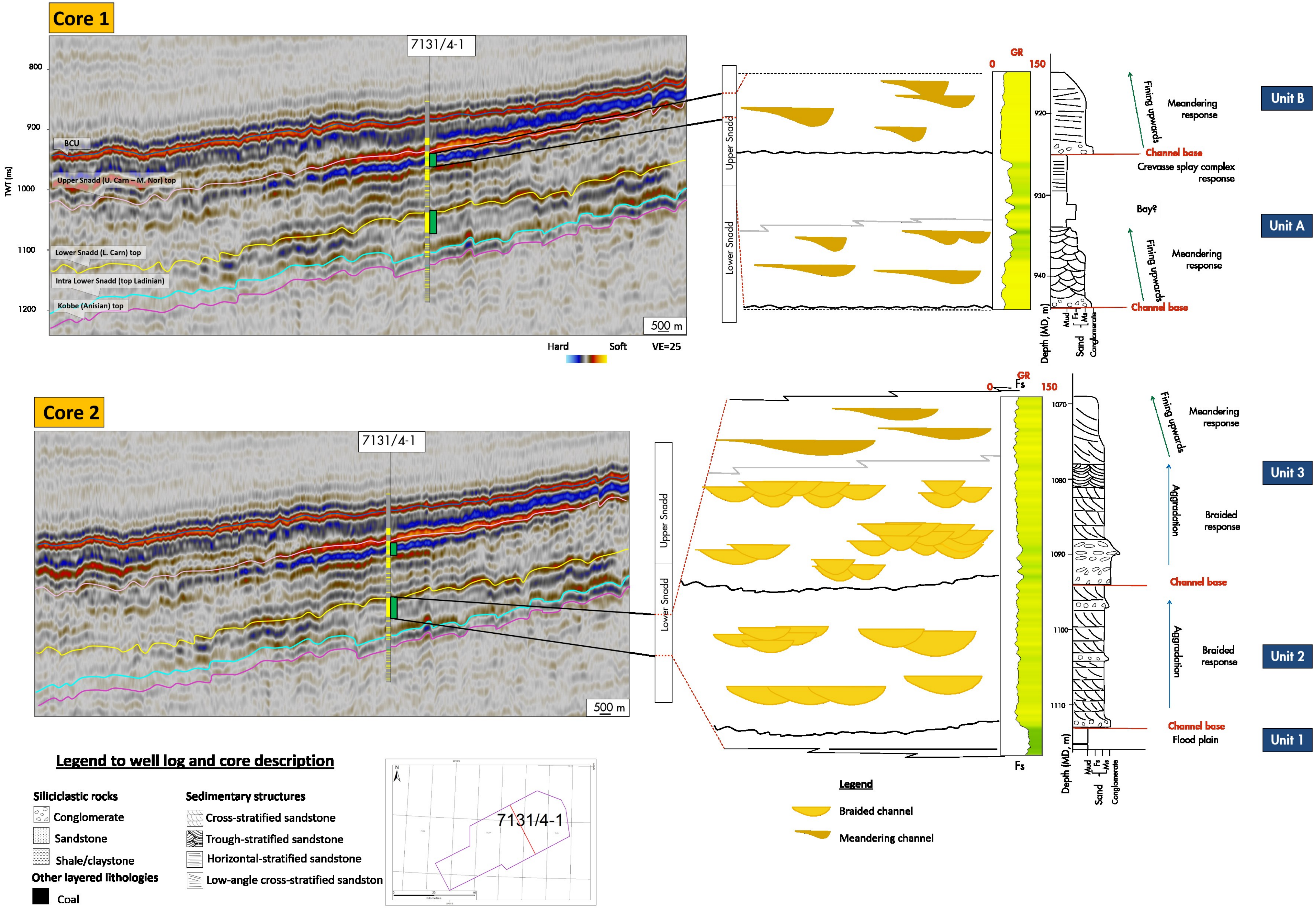


Figure 32: Seismic line trough well 7131/4-1 with the stratigraphic Lower and Upper Snadd sequences and associated well log response and core interpretation.

7.3.2 7228/7-1A core

Well 7228/7-1A is located within the southwestern Nordkapp Basin. The core samples are interpreted to represent multi-story fluvial channel systems in Lower Carnian, and the Ladinian package is interpreted as a tidal channel complex (provided by Norske Shell). As this area of the Nordkapp Basin has not been studied in detail (only the study areas 1, 2 and 3), this is brought into the thesis to demonstrate the presence of fluvio-deltaic activity in the Nordkapp Basin through the Triassic Snadd Formation (Figure 33).

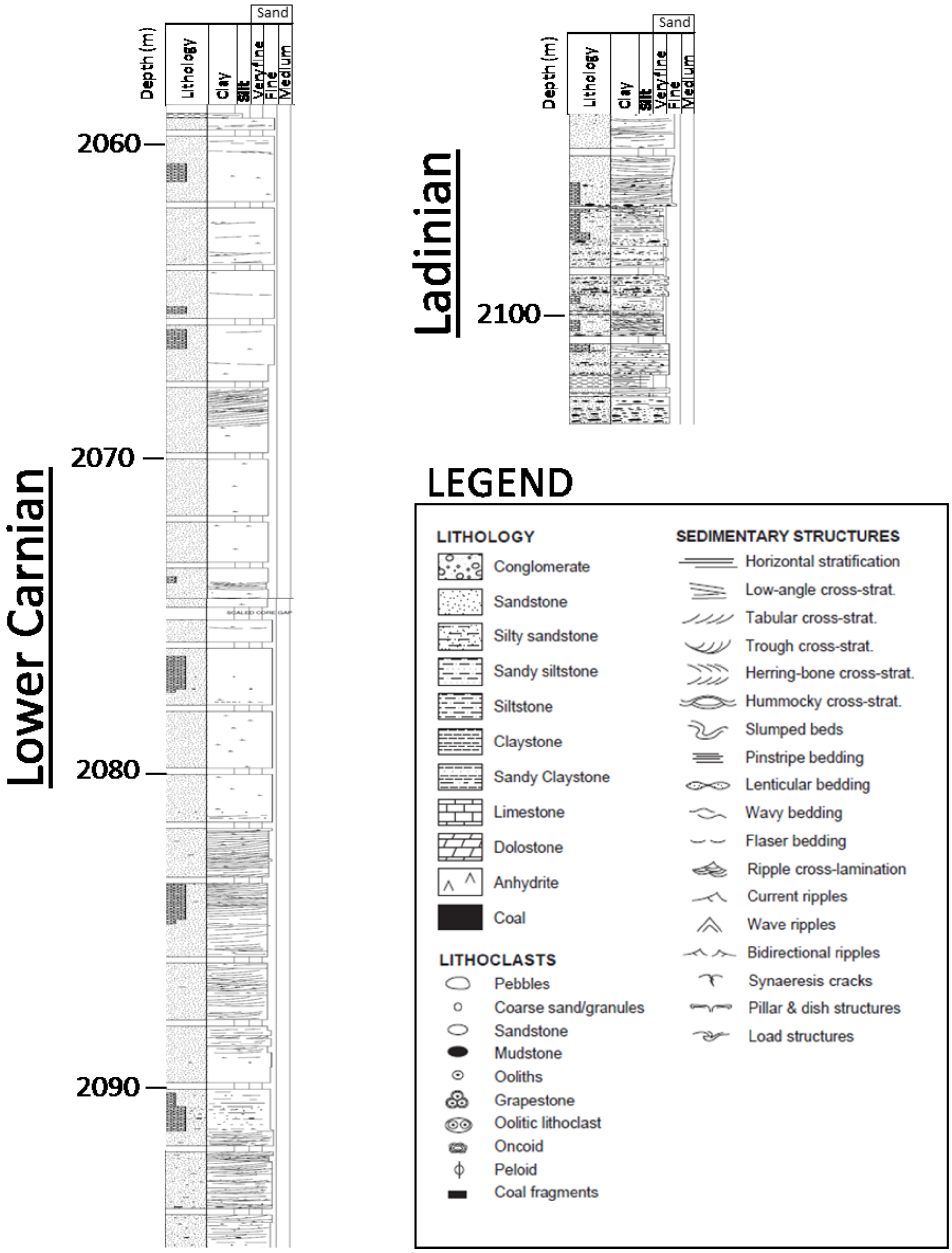


Figure 33: Core interpretation of well 7228/7-1A. The core interval is shown in Figure 13. The core description and interpretations are provided in courtesy of Norske Shell.

7.4 Salt mini-basin stratigraphic architecture and infill-style

7.4.1 Tiddlybanken Basin (Study area 1) fluvial architecture style

The established stratigraphic framework from section *5.0 Stratigraphic Framework* is used in this section. Figures 34-36, are used to describe and illustrate the change in fluvial architecture and style. Interpretations presented in *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)* and *6.1 Structural evolution of the Tiddlybanken Basin* are integrated in the discussion.

Ladinian interval

Description

The lower part of the Ladinian package is onlapping the high to the southwest and the diapir and salt wall to the northeast (figures 34 and 35). Within the Tiddlybanken Basin package, a complex internal termination relationship is present with reflectors that thins out on top of the underlaying reflector (Figure 35). The upper part does thin, but has continued reflectors towards the southwest across the Signalhorn Dome, but is terminating towards the diapir and salt wall. In the Tiddlybanken Basin there are identified features of moderate amplitude that are discontinuous in the seismic sections (<1 km width) and to the south and southwestern area (>1 km width) of the study. These are isolated high amplitude reflectors with poor connectivity (figures 34 and 35).

Along the strike of the Tiddlybanken Basin, internal reflectors partly thin out towards the margins of the basin. As indicated in Figure 36 (map with purple outline), the picked reflector is only present inside the Tiddlybanken Basin. The main depocenter is located in the southeast and is comprised of a thicker unit of the Ladinian package when compared to the northern part of the basin (Figure 36).

Interpretation

The isolated bodies identified in this package are interpreted to be narrow and isolated. The lower part of the package has less amplitude variability, believed to represent distal or prodelta to shelfal systems. This coincides with section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*, where the system is inferred to overall prograde from a shallow marine to lower delta plain environment and the channel-fills have an anastomosing pattern. In the uppermost part of the package in the southeastern area of the rim-syncline, there are successive onlapping of reflectors as the mini-basin sinks adjacent to the growing salt-structure.

Lower Carnian interval

Description

The Lower Carnian package has onlap against the salt diapir and salt wall and against the Signalhorn Dome (from the southwest and inside the mini-basin). The package is overall thinning over the Signalhorn Dome. Several bodies with discontinuous and strong soft amplitudes are identified. These are mainly clustered and stacked in the mini-basin or to the north and west of the Signalhorn Dome. The features have an average width >1 km (figures 34 and 35).

Along the strike of the deepest parts of the basin, the high amplitude soft reflectors are thinning towards the edges of the basin (Figure 36). In the same figure, attribute maps illustrate that these reflectors are not present on the elevated areas in the survey. Two main depocenters are identified in the southeast and northwestern part of the salt mini-basin.

Interpretation

The thickened package with onlapping reflectors towards the Tiddlybanken Basin salt diapir and (southwest of) the Signalhorn Dome, imply that the Signalhorn Dome and the Tiddlybanken Basin salt diapir were highs during this time (additionally supported in section *6.1 Structural evolution of the Tiddlybanken Basin*). It is inferred that there was erosion of the package on the top of the Signalhorn Dome and possibly of the Tiddlybanken Basin salt diapir and salt wall. Channel-infills are located in the rim-syncline and to the west of Signalhorn Dome. The channel bodies in the salt mini-basin are interpreted to be wide and thick, and believed to be stack vertically, likely forming an amalgamated package representing a multistorey channel complex. These systems are laterally extensive and are interpreted to have a channel belt architecture with a total width of 7-8 km. As a result of multiple active channels it is believed to be composed of multi-story channel-fill complexes (as interpreted in section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)).* In comparison, the channel fills interpreted to the southwest of the Signalhorn Dome have a different fluvial style and are expected to have poor connectivity. Considering the depocenter of Ladinian time and the depocenters of Lower Carnian, the creation of northwestern depocenter is believed to be a result of progradation of the fluvio-deltaic system within the rim-syncline (as a second depocenter is shifted northwest).

U. Carnian to M. Norian interval

Description

The Tiddlybanken Basin sequence has several reflectors that onlap the older sequence and internally thins on top of the reflectors below, mainly towards the salt diapir and salt wall. It is also identified stratal onlap towards the Signalhorn Dome from the south and southwest. There are bodies characterized by soft and discontinuous amplitude reflectors, mainly in the mini-basin, in addition to areas north, south and west of the Signalhorn Dome. The dimensions of the features in the mini-basin are estimated to be 500 m wide (average) and the south to southwestern area is dominated by bodies that are 1-1.5 km wide. The clustering bodies in the mini-basin are moderately laterally extensive (particularly in the southeastern part of the mini-basin), and bodies located elsewhere are rather isolated.

Several soft reflectors are thinning out of from the middle of the Tiddlybanken Basin to the edges of it. Some reflectors (as indicated in Figure 36) are only locally present inside the Tiddlybanken Basin. There is an elongated depocenter in the middle of the Tiddlybanken Basin (Figure 36).

Interpretation

The identified onlapping reflectors at the base of the package are present within the Tiddlybanken Basin and southwest of the Signalhorn Dome, implying that the Signalhorn Dome was a high during this time (additionally supported in section *6.1 Structural evolution of the Tiddlybanken Basin).* As a result of the uplift it is assumed that some of the sediments on top of the Signalhorn Dome have been removed due to erosion (thinner sequence here). Fluvial channels are identified mainly in the lower part of the sequence in the northern area of the mini-basin, and the southern part has a greater abundancy of channelized bodies. These are narrow and thin, but are interpreted to be laterally distributed in the southern part and representing an anastomosing fluvial system. As the depocenter of this sequence was focused to the central part of the Tiddlybanken Basin, there is limited presence of channels in the northern part of the basin compared to the central part (figures 34 and 35).

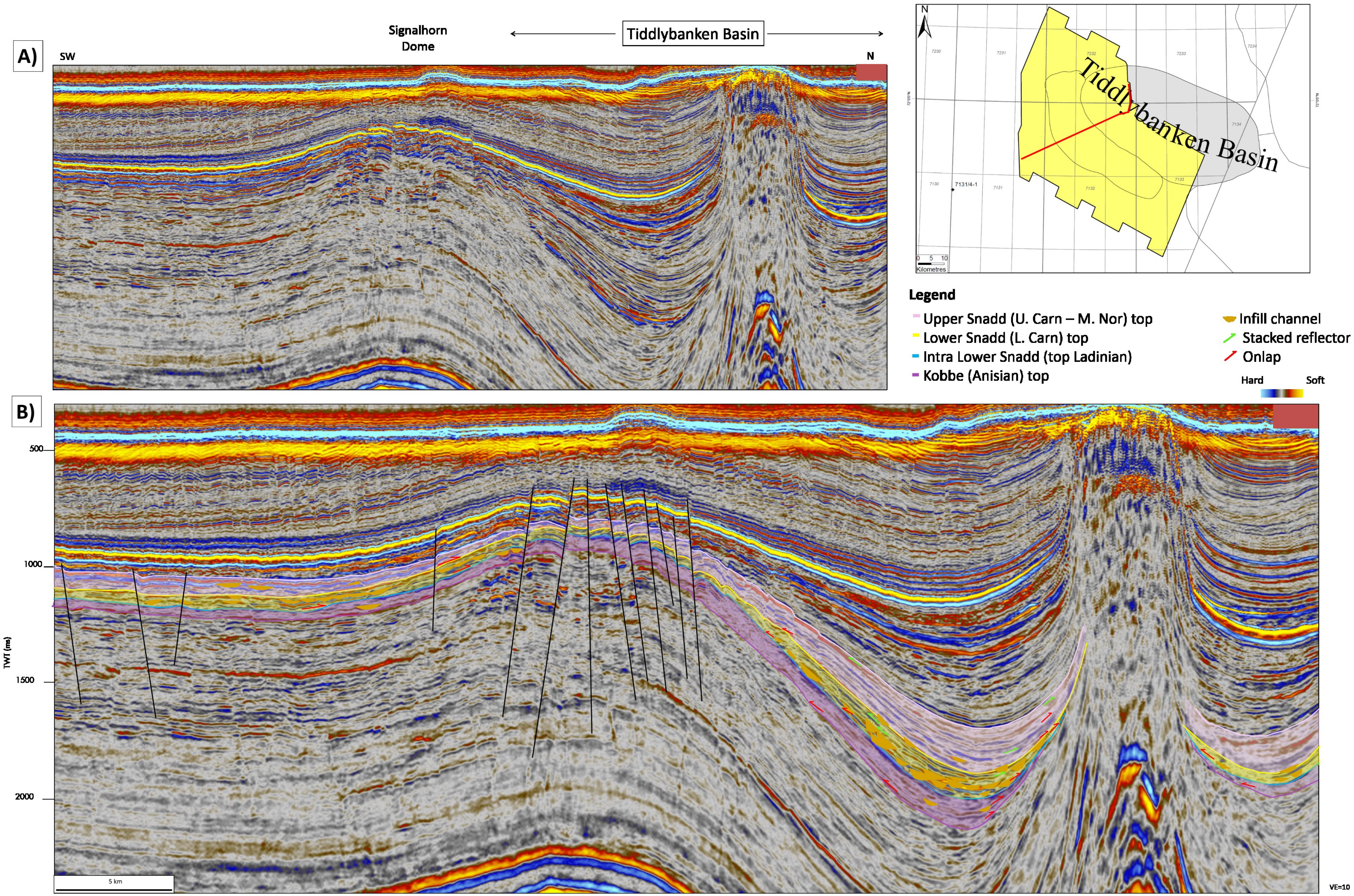


Figure 34: Demonstrates the stratigraphic architecture and infill style through «Study area 1» from SW to N.

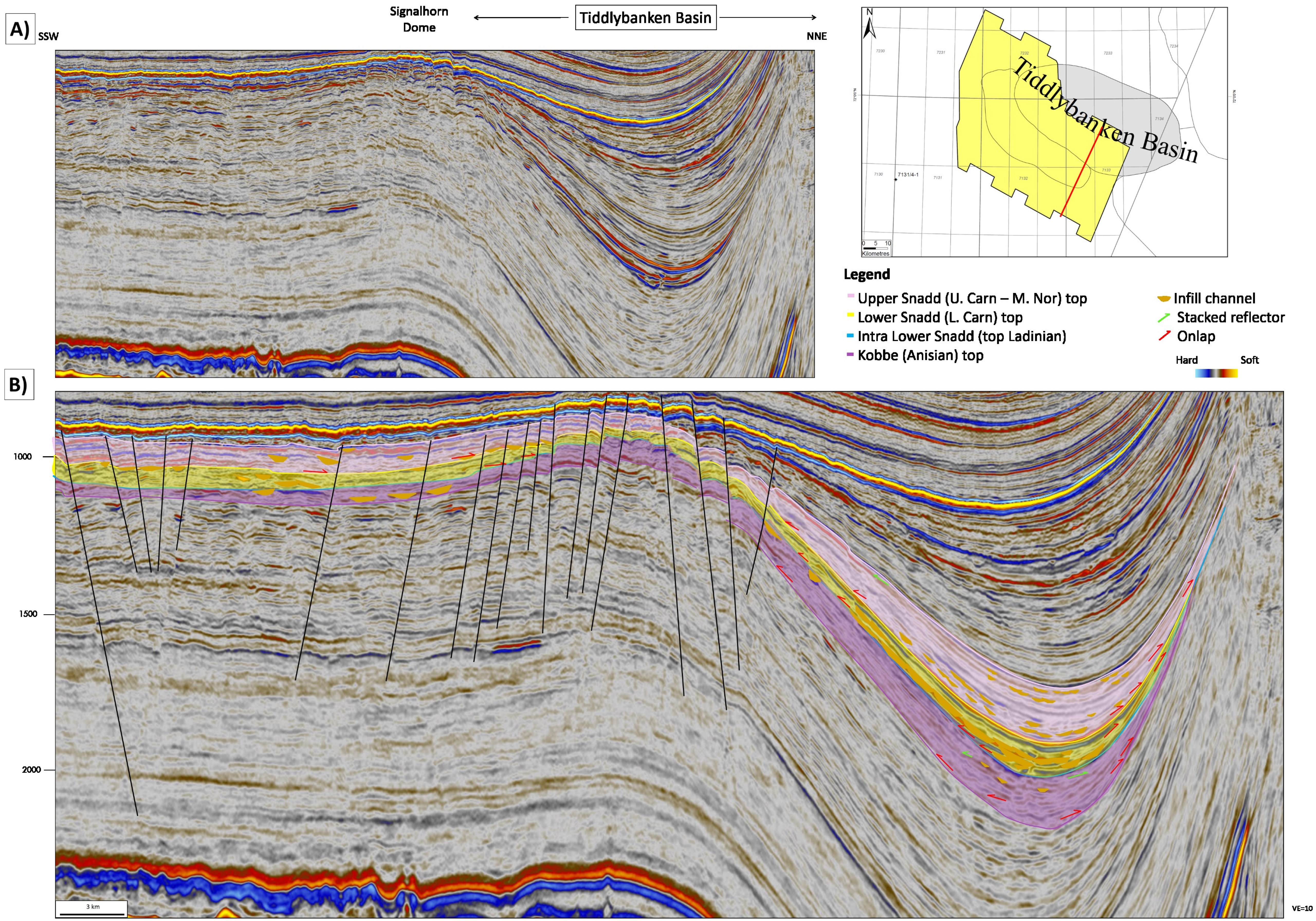


Figure 35: Demonstrates the stratigraphic architecture and infill style through «Study area 1» from SSW to NNE in the eastern part of the survey.

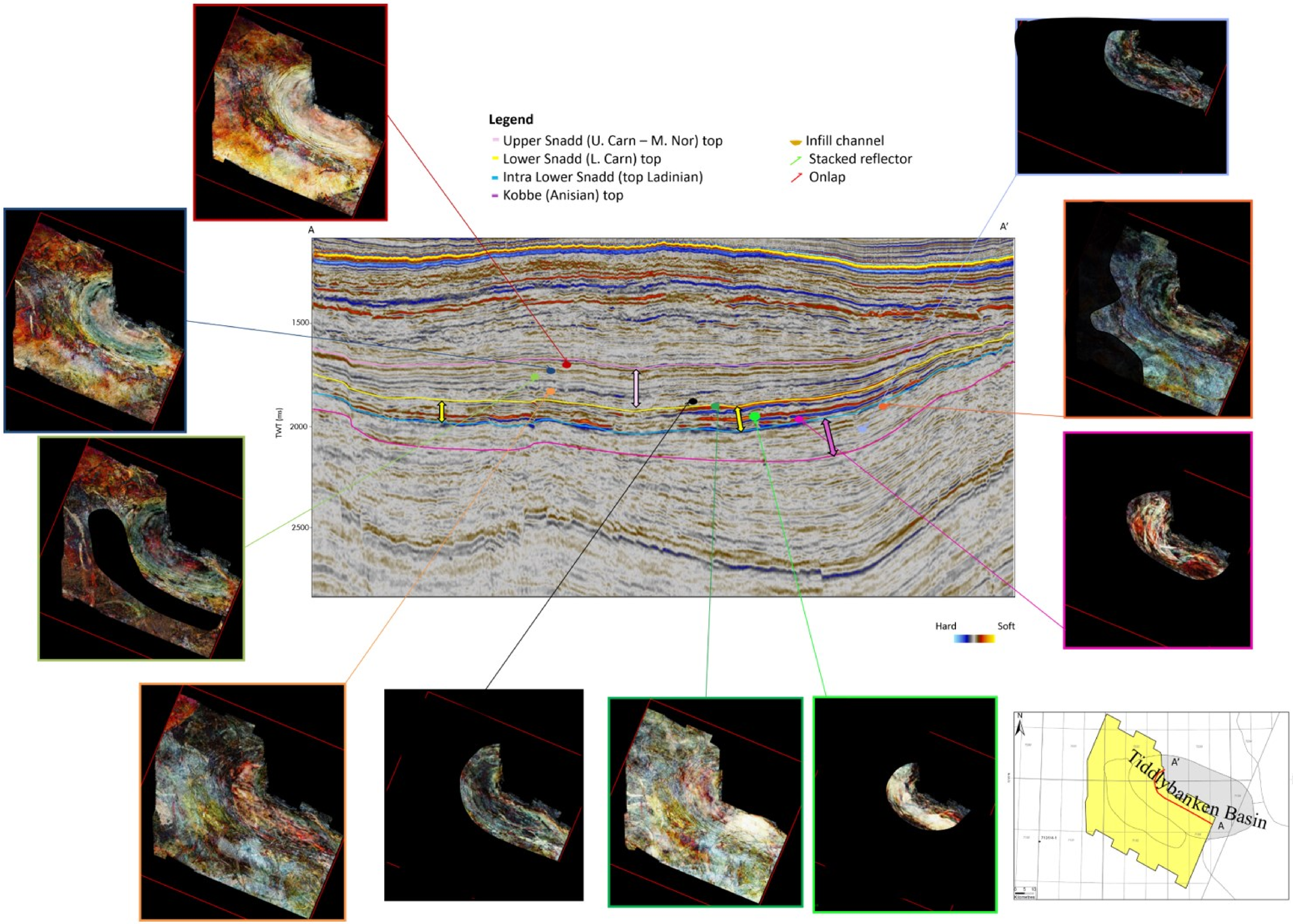


Figure 36: Seismic line through the deepest parts of the Tiddlybanken Basin illustrating the shift in depocenters through the stratigraphic sequences of the Triassic Snadd Formation.

7.4.2 Nordkapp Basin (Study area 2) fluvial architecture style

The established stratigraphic framework from section *5.0 Stratigraphic Framework* is used in this section. Figures 37 and 38, are used to describe and illustrate the change in fluvial architecture and style. Interpretations presented in Sections *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)* and *6.2 Structural evolution of the Nordkapp Basin* are integrated in the discussion.

<u>Ladinian interval</u>

Description

The Ladinian package has a uniform thickness in the hanging wall (Nordkapp Basin; wellbore 7228/2-1S) and footwall (Bjarmeland Platform; wellbore 7228/1-1) (figures 37 and 38). Disconnected high amplitudes are located mostly in the upper part of the package, and are isolated. The width is identified to be approximately 100-500 meters.

Interpretation

The constant thickness inside the Nordkapp Basin and the western flank is interpreted to be a result of uniform differential subsidence (concurring with section *6.2 Structural evolution of the Nordkapp Basin*). The features identified are interpreted as anastomosing to meandering narrow channel-fills (also documented in section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*. This corresponds well with the established interpretation of the Ladinian, which is considered a progradational unit. The GR-log response coincides with a coarsening upwards trend, where the upper part of the package is more sand-rich.

<u>Lower Carnian interval</u>

Description

The package is uniform, both in the central and southern part of the study (figures 37 and 38). Broad, connected and high amplitude bodies are identified. These bodies are laterally extensive (up to 1-2 km wide) and clustered in the lower to middle part of the unit. Notably discontinuous amplitude variations are found in the footwall in the southern cross-section, and in the hanging wall these are stable and continuous reflectors (figures 37 and 38).

Interpretation

There are no thickness variations or stratal terminations identified in the package. The Early Carnian was likely a stable period, that did not experience salt piercement (coincide with results from section *6.2 Structural evolution of the Nordkapp Basin)*. The high and soft amplitudes represent fluvial channel infill, and from the section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian),* the identified channel fills are interpreted to have a width greater than 1 km.

The channelized systems are penetrated by the two wells, with sandy-rich units at the base that fine upwards (figures 37 and 38). Within the Nordkapp Basin, the package (in well 7228/2-1S) shows an amalgamated basal part that fine upwards (figures 13 and 37). The western well (7228/1-1) has the same trend, however the GR-log response is interpreted to have a typical point-bar fining upward trend (with limited to no amalgamation) (figures 13 and 37). It is expected that multistory sandy channel-fills or more amalgamated bodies are present in the hanging wall. As an implication, the channel fills are more connected. The overall depositional cycles of progradation and retrogradation fits with this interpretation (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)* and Figure 13).

<u>U. Carnian to M. Norian interval</u>

Description

The Upper Snadd sequence is present with different thicknesses in the footwall and hanging wall. The sequence in the hanging wall is thicker, and has a lower unit with slightly different facies (compared to the overburden) that is not present at the on the Bjarmeland Platform (illustrated and indicated in figures 37 and 38). The facies of the upper unit are correlated inside the Nordkapp Basin across and in the Bjarmeland Platform. The upper unit to the west has a reflector that is onlapping the Top L. Carnian reflector (MFS) (Figure 37). The sporadic and discontinuous reflectors in the southern part of the survey make it difficult to identify any stratal terminations in the sequence.

The lower unit consists of semi-continuous high and soft amplitudes, which can be up to several hundred meters wide. The upper unit has isolated and scattered bodies, that are thinner and narrower compared to the underlying unit. Overall, there is a greater abundancy of bodies within the Nordkapp Basin. The bodies are isolated in the upper unit, and the lower unit has greater lateral and vertical connectivity in the hanging wall.

Interpretation

The Nordkapp Basin has a lower unit of the U. Carnian to M. Norian sequence, which is not present at the Bjarmeland Platform. This is a result of Late Carnian salt movement, initiating faulting at the margin of the Nordkapp Basin with increased rates of differential subsidence across the boundary fault (see section *6.2 Structural evolution of the Nordkapp Basin*). This led to increased accommodation space in the hanging wall, that was occupied by fluvial channel systems. It was not possible to extract information about the geomorphology of the paleo-channels of the lower unit (section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)),* therefore the dimensions, thickness, distribution and connectivity of the channel-fill remain uncertain (as indicated with question-marks in figures 37 and 38). The middle part of the upper unit is dominated by narrow channels that have poor to possibly some channel interconnectivity. The fluvial style is interpreted to be meandering to anastomosing. The GR-log response of the upper unit (figures 13 and 37), coincide with the findings in the attribute maps and the fluvial style that suggest that the area is occupied by a lower delta plain environment. The 72287/1-1 well has a greater amount of fine-grained sediments compared to well 7228/2-1S, supporting this theory. The lower unit has a more sandy-rich response, and is expected to have a greater proportion of sand bodies preserved in the Nordkapp Basin (figures 13 and 37).

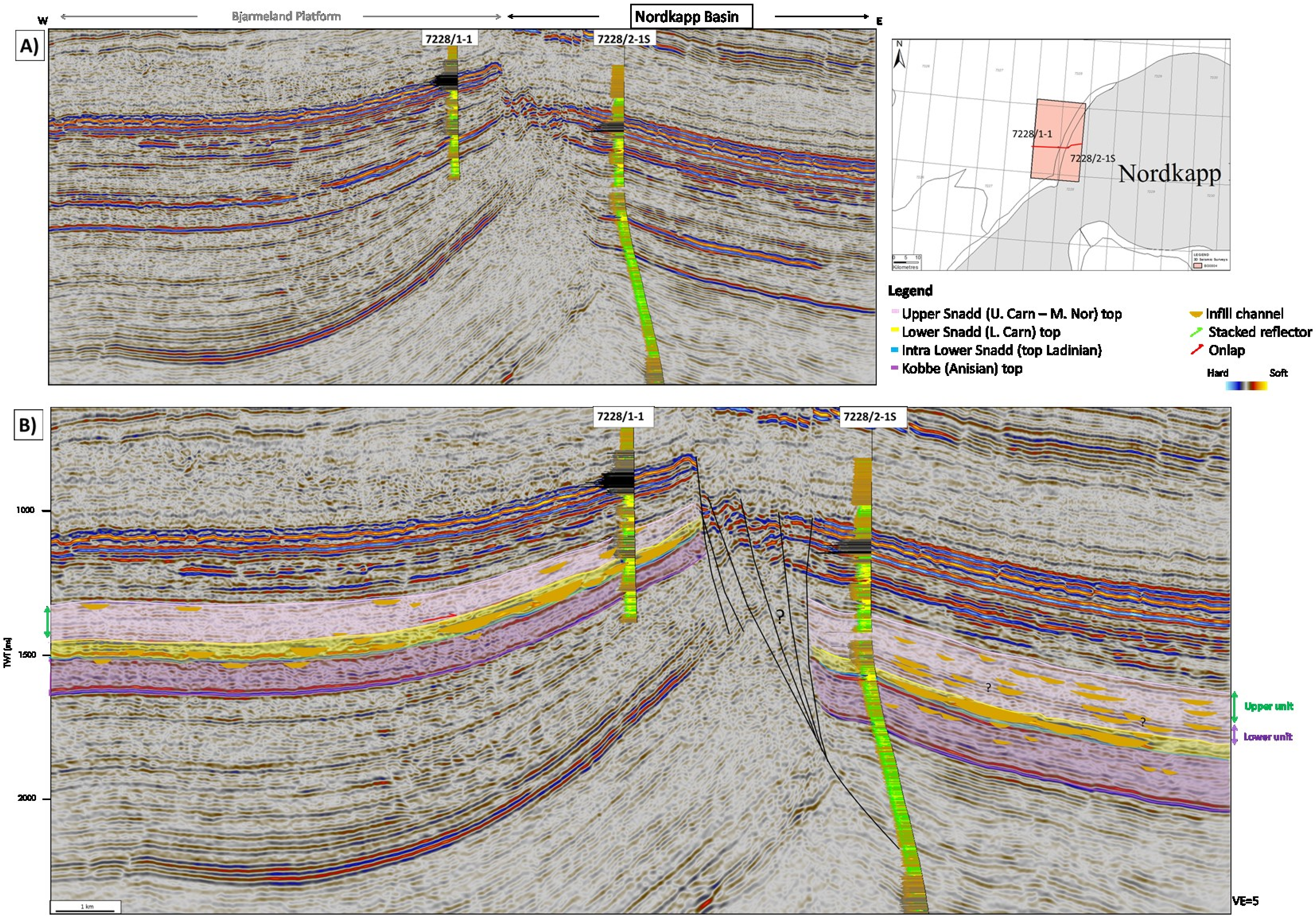


Figure 37: Demonstrates the stratigraphic architecture and infill style through «Study area 2» from W to E through the 7228/1-1 and 7228/2-1S wells. The width and stratigraphic presence of channel infills are based on seismic facies analysis and stratal slicing using attribute maps on every reflector. The Upper Snadd sequence is sub-divided into two units as indicated in the figure, and the lower unit is only present in the Nordkapp Basin. It was not possible to resolve any fluvial styles in the in the Lower unit in the attribute maps, and therefore the thickness, distribution and connectivity of the channel-fill remain uncertain (indicated with question marks in the figure).

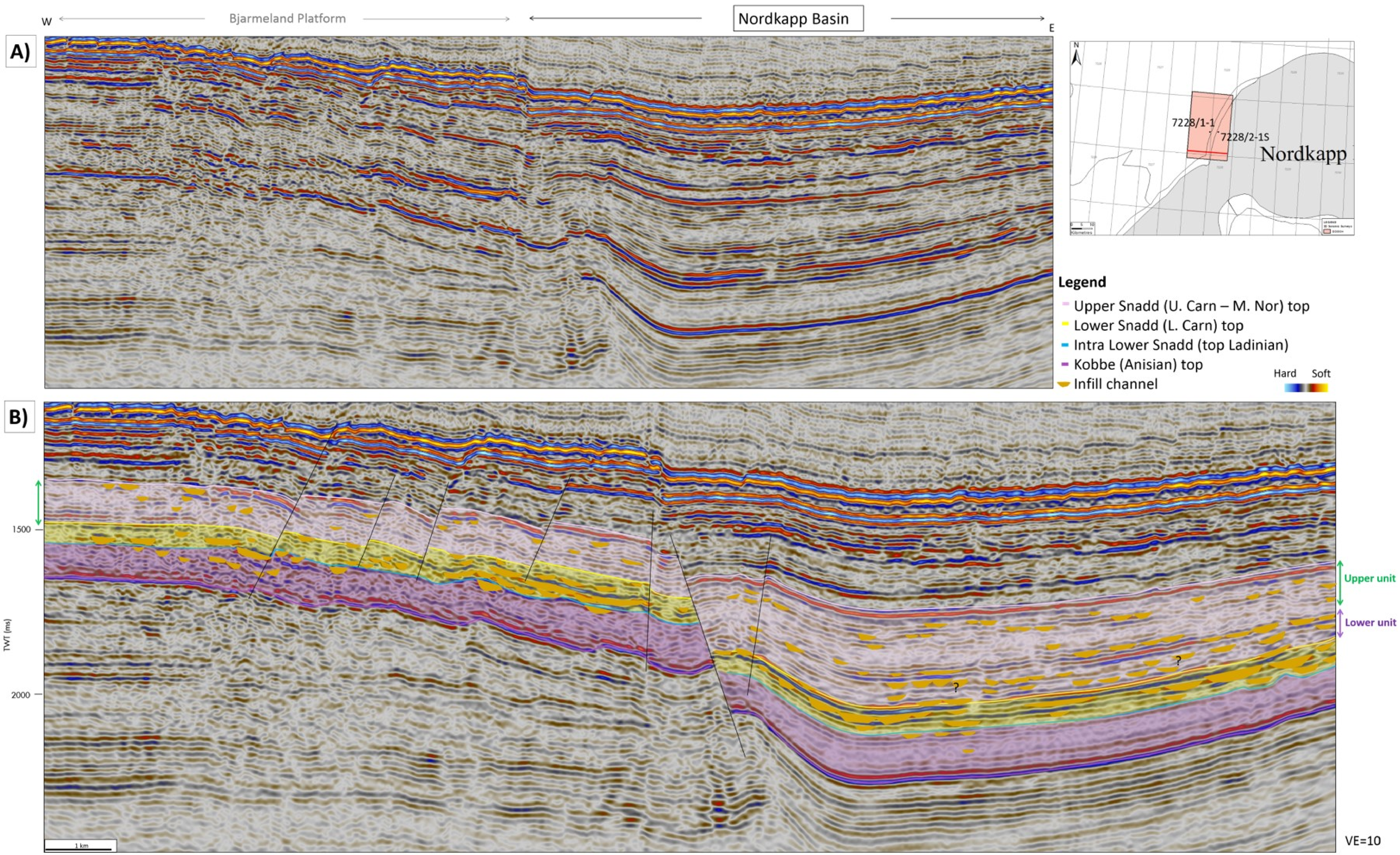


Figure 38: Demonstrates the stratigraphic architecture and infill stylefrom W to E in the southern part through «Study area 2». The width and stratigraphic presence of channel infills are based on seismic facies analysis and stratal slicing using attribute maps on every reflector. The Upper Snadd sequence is sub-divided into two units as indicated in the figure, and the lower unit is only present in the Nordkapp Basin. It was not possible to resolve any fluvial styles in the in the Lower unit in the attribute maps, and therefore the thickness, distribution and connectivity of the channel-fill remain uncertain (indicated with question marks in the figure).

8.0 Discussion

The discussion integrates results from attribute maps, well correlation and core samples to evaluate: i) the structural evolution and; and ii) resultant spatial and lateral variability of fluvial infill pattern and stratigraphic architecture in the salt mini-basins. The hydrocarbon potential is also addressed.

8.1 Fluvial style and paleogeography of E. Ladinian to M. Norian

The evolution of the Triassic Snadd Formation in the Barents Sea is documented by several workers (e.g. Glørstad-Clark 2011, 2010; Henriksen et al., 2011; Klausen et al., 2015; Klausen, 2013; Riis et al., 2008). As a result of uplift and erosion of the Eastern Barents Sea-Kara Sea, Novaya Zemlya orogeny, region in Carnian times, large coastal plain environments extended to the western parts of the Barents Sea basins and platforms (Smelror et al., 2009). As a result, the identified salt (mini-)basins development is partly controlled by differential sediment loading from the regional fluvial system.

The depositional environments of the Snadd Formation in study areas are controlled by the regressive and transgressive cycles; are two R-T mega-sequences representing forestepping to backstepping fluvio-deltaic clastic wedges the Snadd Formation. Depositional environments range from upper delta plain to marine environments, but the study areas are mostly occupied by flood- and delta plain environments with fluvial channel systems (Figure 39).

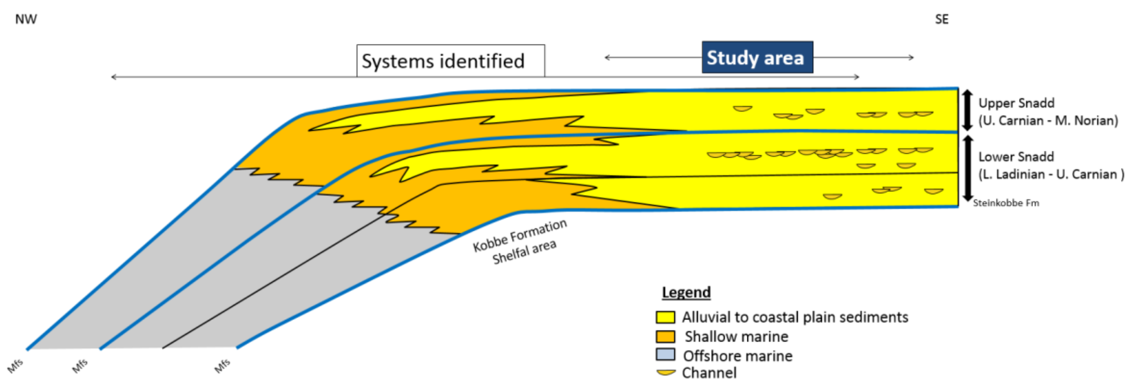


Figure 39: Conceptual model of depositional sequences identified in the study areas.

Paleogeographic reconstruction

By using the attribute maps, it was possible to interpret the channelized systems within the study areas and correlate the high amplitudes to construct a paleogeographic reconstruction of maximum fluvio-deltaic progradation in Lower Carnian (Figure 40). Additional amplitude maps were provided in courtesy of Norske Shell (surveys ST14006 and SH9102) to generate a paleogeographic reconstruction of the interval.

The interpreted channel systems have a prominent character of anastomosing, meandering, braided with meanders and braided (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*). The fluvial channel systems are sourced from the south to southeast and are oriented north to northwest. Within the Nordkapp Basin there are a fluvial systems trending in a west-southwestern direction (with an unknown source area). The fluvial channels and channel belts are wider in the southeast, and become narrower towards the northwest. The channel systems deliver sediments to the salt mini-basins within the Tiddlybanken and Nordkapp basins. In Figure 40, a paleogeographic reconstruction of the E. Carnian time illustrates the change in fluvial style, and how the systems extend from one salt basin to the next.

The salt related study areas are affected by fluvio-deltaic interaction with salt diapirism (Figure 40). The channel belt that enters the Tiddlybanken Basin is expected to split into two mini-basins alongside the elongated salt wall and diapir. In this present study, 3D data is available in the southwestern part of the Tiddlybanken Basin and therefore only one mini-basin is identified within the basin. The channel systems are expected to extend beyond the Tiddlybanken Basin, across the eastern Finnmark Platform and into and across the Nordkapp Basin Study area 2. The wide scroll-bar complex on the southern part of the Finnmark Platform represents another system feeding the northeastern sub-basin of the Nordkapp Basin. These systems are expected to deliver huge sediment supply and to fill the accommodation space generated in the Nordkapp Basin in response to salt tectonics, before exiting the basin and extending further onto the Bjarmeland Platform.

The salt appears to have moved repeatedly, and is partly diachronous at the different stratigraphic levels. This generates depocenters at different locations and times within the basin. The fluvial channels inside are located between the diapirs and follow the topography.

According to the Norwegian Petroleum Directorate (2013) rim-synclines formed around the salt bodies with thick sequences of Triassic sediments close to the diapirs, in the Tiddlybanken and Nordkapp basins. It is argued that in the Tiddlybanken Basin fluvial and deltaic systems likely were attracted to these rim-syncline basins entering the basins from the east-southeast and oriented northwest, as also identified in this thesis. These resultant fluvial channel-fills form candidate reservoir targets in the basins. The fluvial channel systems extend beyond the basins and at least one exit point for the fluvial systems is captured within Study area 2. The amplitude maps of Study area 2 reveal channelized systems that continue to extend in a northwestern direction outside the margin of the Nordkapp Basin, and at one point it will gradually transition into a more coastal plain setting (Figure 40).

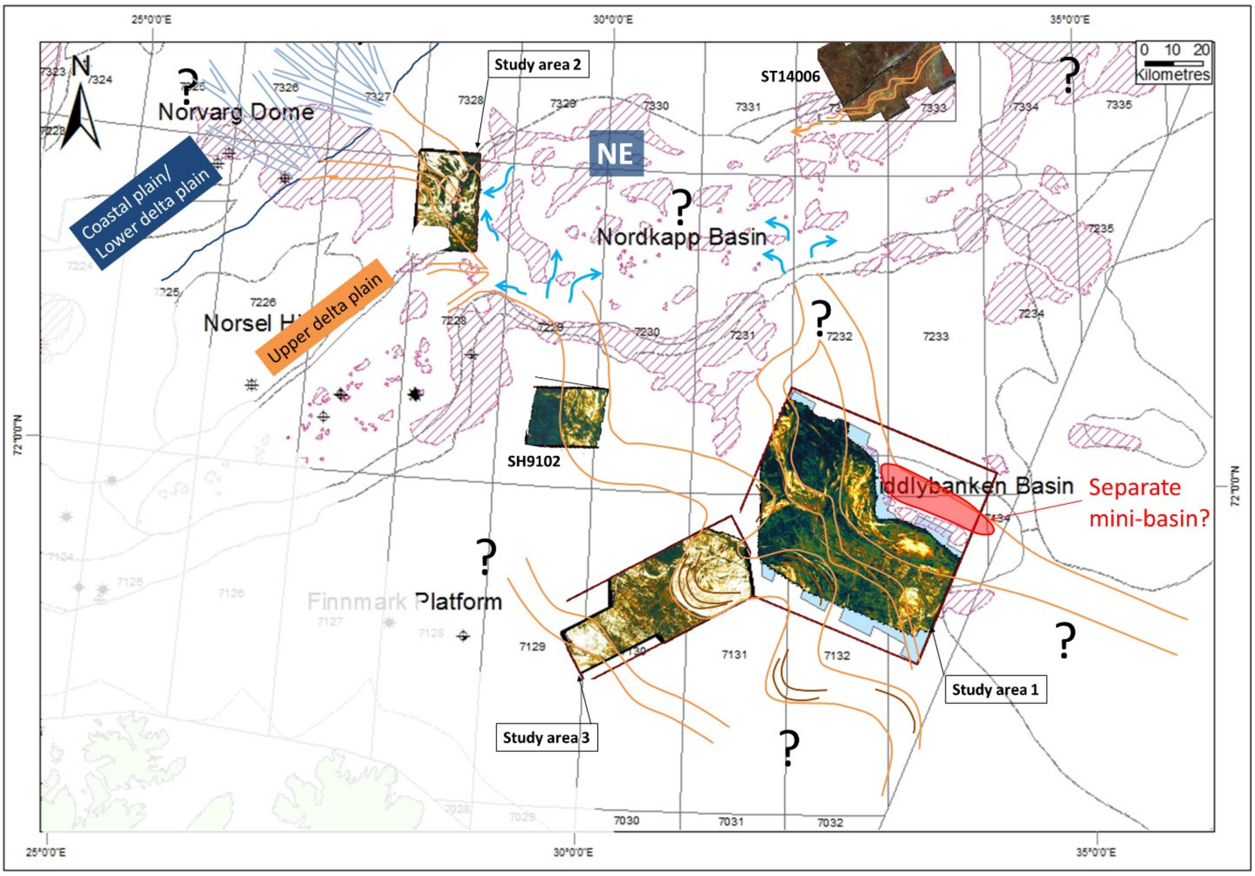


Figure 40: Paleogeographic reconstruction of Early Carnian time using study area 1, 2 and 3. Additional amplitude maps from surveys ST14006 and SH9102 are provided in courtesy of Norske Shell.

Fluvial styles of the M. Triassic – L. Triassic Snadd Formation

The fluvial styles of the Triassic Snadd Formation have been the focus in several studies (Bugge et al., 2002; Glørstad-Clark et al., 2011, 2010; Klausen et al., 2015; Klausen, 2013; Riis et al., 2008; Smelror et al., 2009). Recently Klausen et al. (2015) described the regional development, sequence stratigraphy and fluvial styles of the M. Triassic – L. Triassic Snadd Formation. This author favored fluvial systems interpreted as meandering to anastomosing. However, by studying the sequences in more detail it is evident that this is a more complex mixed fluvial system (spatially and temporally), which is interpreted within this present study of the Snadd Formation. Evidence from core data (well 7131/4-1), well logs and attribute maps indicate that the fluvial systems are more dynamic than first anticipated, with core data interpreted as typical braided river infill (bars), with large meanders as evident by the amplitude extracts. The fluvial channel types change with movement, from proximal to distal depositional environments.

Within the Lower Carnian package, there is identified a scroll-bar apart of a wide meander-belt in the attribute maps of the stable platform area of Study area 3. The core interval (of well 7131/4-1) within the Lower Snadd Formation reveals the presence of facies associated with stacked braided fluvial systems. The core (2) interval, mainly consists of braided units, though the uppermost unit has a typical meandering response (see section *7.3 Well Inspection*). The results of the attribute maps of this section display a wide scroll-bar, even though only 8 meters of total 48 meters of the unit is represented by expected meandering response. As a result of this, the underlying braided system is likely the channel system seen exiting in the northwestern part of the scroll-bar (Figure 30 FL3). Since only the meandering systems are displayed within this interval it is believed that it is an artifact, as it is clear that the interval is not dominantly meandering. In consort, this suggest a fluvial style more towards a meandering braided system, i.e. a braided river system with large meanders (see Figure 41, type number 3).

The fluvial style and architecture is noticeably different (figures 34, 35, 37 and 38) in the identified salt mini-basins relative to the stable platforms: in the salt mini-basins vertical stacking is abundant in the upper part of Lower Snadd mega-sequence, and lateral stratigraphic development on the platform areas. The interpreted channel-fills in the salt mini-basins are affected by increased subsidence generated as a result of diapiric growth and resultant localized systems that generate different fluvial styles and subsequently architecture. I.e., in Early

Carnian the mini-basin of the Tiddlybanken Basin was occupied by a braided system with meanders (see section *7.2 Attribute maps of Middle to Late Snadd (E. Ladinian – M. Norian)*), while platform areas are dominantly meandering. Timing of salt growth in the Nordkapp Basin sub-basins are evaluated to partly overlap, as the salt movements in the Nordkapp Basin are established to have happened at an earlier stage than in the Tiddlybanken Basin. In Study area 2, there is identified meandering channel-fills and additionally a braided-like fluvial character in Lower Carnian, illustrating a slightly different fluvial character than what was described by Klausen et al. (2015).

Downstream change in fluvial style illustrated from the analogue modern Irrawaddy River (Myanmar) (Figure 41) illustrates the expected east-west changes in fluvial channel systems identified through the Snadd Formation; these represent a change from a proximal to a distal part of the downstream system. The dimensions and channel type variability of the modern day Irrawaddy River corresponds well with the fluvio-deltaic systems identified in eastern Barents Sea (from east to west). The Irrawaddy River also meets the expectation of arid-humid climate belt participation inferred for the Triassic Snadd Formation. The different channel types illustrate mixed channel types, going from low sinuosity braided rivers, to braided with meanders to meandering with point bars to a wet environment with stable anastomosing channels.

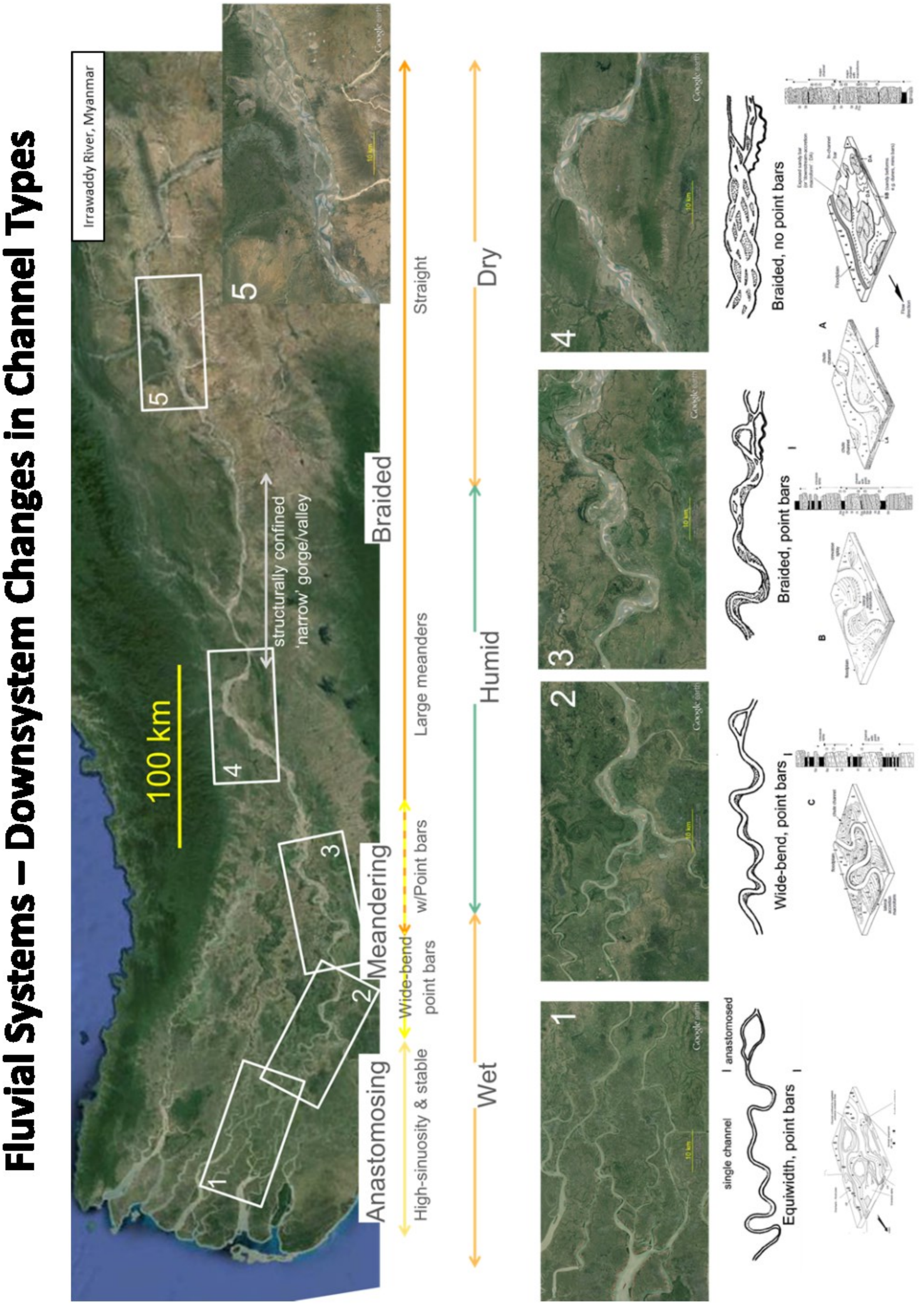


Figure 41: The Irrawaddy River (Myanmar) is an analogue of the Snadd channelized systems. This modern day river illustrates the main channel types identified, in addition to a mixture of the identified fluvial systems. This figure is provided in courtesy of Norske Shell.

8.2 Evolution of salt mini-basins in the Tiddlybanken and Nordkapp basins

8.2.1 Controlling salt movement mechanisms in selected salt basins

The Greater Nordkapp Basin

The southwestern part of the Nordkapp Basin has an orientation towards north north-east and the strike orientation of the northeastern part is northeast. These two sub-basins display similarities, but there are differences in main diapiric growth intervals when comparing them. For both sub-basins there are abundant salt diapirs with rim-synclines and salt mini-basins in the middle of the basin. The middle of the sub-basins has experienced more subsidence than what is established on the basin margins due to larger quantities of salt diapirs and greater salt piercement activity. However, the Southwest sub-basin has experienced (an earlier) diapiric growth in Early Triassic (Havert and Klappmyss formations), whereas the Northwest sub-basin has its main growth interval in Middle Triassic Kobbe Formation. This can indicate that the Nordkapp Basin does not behave like a single basin entity when it comes to the salt tectonics, but rather as two different sub-basins with its own controlling mechanisms for salt movement. Timing of subsidence and sedimentation was different the two sub-basins; the Northeast sub-basin experienced diapiric growth (and therefore more subsidence and accommodation space) through Middle to Late Triassic (mainly Kobbe and Snadd formations). The southeastern basin had its main growth in Early to Middle Triassic. As a result of the different behavior in the sub-basins, the Nordkapp Basin can be split into two distinct sub-basin bodies, which are in the present day connected.

As a consequence of increased subsidence rate through the Snadd interval in the northeastern basin, it is expected that the described fluvio-deltaic systems accumulate in this sub-basin. These will consist of large fluvial channel systems through the Middle to Late Triassic Snadd Formation, as illustrated in the paleographic reconstruction of Lower Carnian (Figure 40).

Initiation of salt movement mechanisms in study areas 1 and 2

According to Nilsen et al. (1995) the major tectonic events in the Barents Sea have controlled the initiation, growth and reactivation of the salt diapirs in the Nordkapp Basin. Other authors believe that differential loading of sediments initiated the salt diapirism to create nearly vertical salt diapirs that reached or almost reached the delta plain (Norwegian Petroleum Directorate, 2013; Bjørlykke, 2010). As the fluvio-deltaic systems build into the Southeast sub-basin, there are thicker rim-syncline packages in the lower stratigraphic levels in the southeastern margin. This might be a result of differential loading within the sub-basin as the fluvial system extended, and earlier salt growth. Additionally, younger faults related to salt-pillow growth along the Nordkapp Basin in Study area 2 have been identified, which have likely been triggered due to salt evacuation. Early to Middle Triassic sequences in the central parts of the sub-basins in the Nordkapp Basin have evidence of faulting as a result of salt diapir growth. Study area 1, Tiddlybanken Basin has its initial diapiric growth due to differential loading as it shows no evidence of basement faulting or faulting on the sides of the diapir.

The initiation of salt movement in the Nordkapp Basin is interesting and much disputed. However, considering that this is not of great importance to the Triassic Snadd Formation, present study does not examine this topic further.

8.2.2 Mini-basin infill-pattern, architecture and style in selected salt basins

External factors such as climate and sediment source area affect the rate of sediment supply delivery, and therefore control available sediments, type and composition. This is a response to the interplay in combination with drainage pathway and subsidence rate of the area. Together, these parameters change the expected nature of deposits and basin-infill style. In a situation where the sediment delivery rate is balanced with the subsidence rate, it is expected that the fine-grained overbank material will be carried away and reworked by channels migrating laterally connected, resulting in channel-fill that is dominantly sand-prone. In case the sediment influx rate is less than the subsidence rate, the channels are not anticipated to rework and remove the overbank deposits, and rather preserve the fining-upwards sequences. This leads to isolated and vertical channel-fill deposits. Lastly, if the sediment input is greater than the subsidence rate, the system will likely rework the sediments, leaving only lags of pebble. At this stage, the reservoir quality is poor (Banham and Mountney, 2013b) (figures 42 and 43).

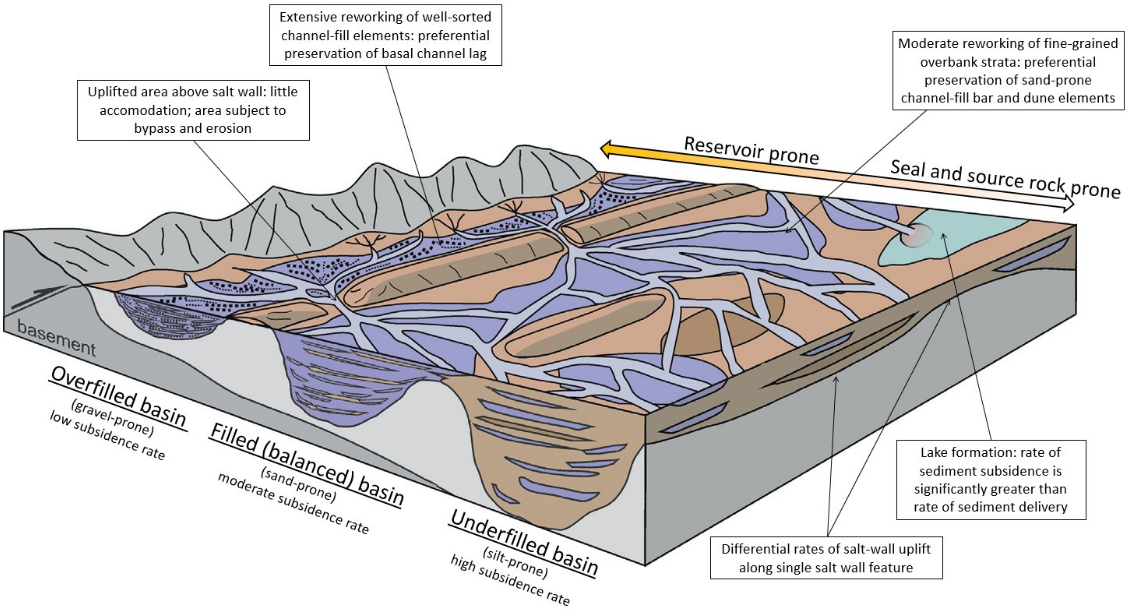


Figure 42: Conceptual model of basin infill-style based on overfilled, filled and underfilled basin conditions. It represents constant sediment delivery rate with varying accommodation space created, and illustrates how these parameters control the spatial and lateral variability of fluvial styles and architecture in a salt-mini basin (modified after Banham and Mountney, 2013 b).

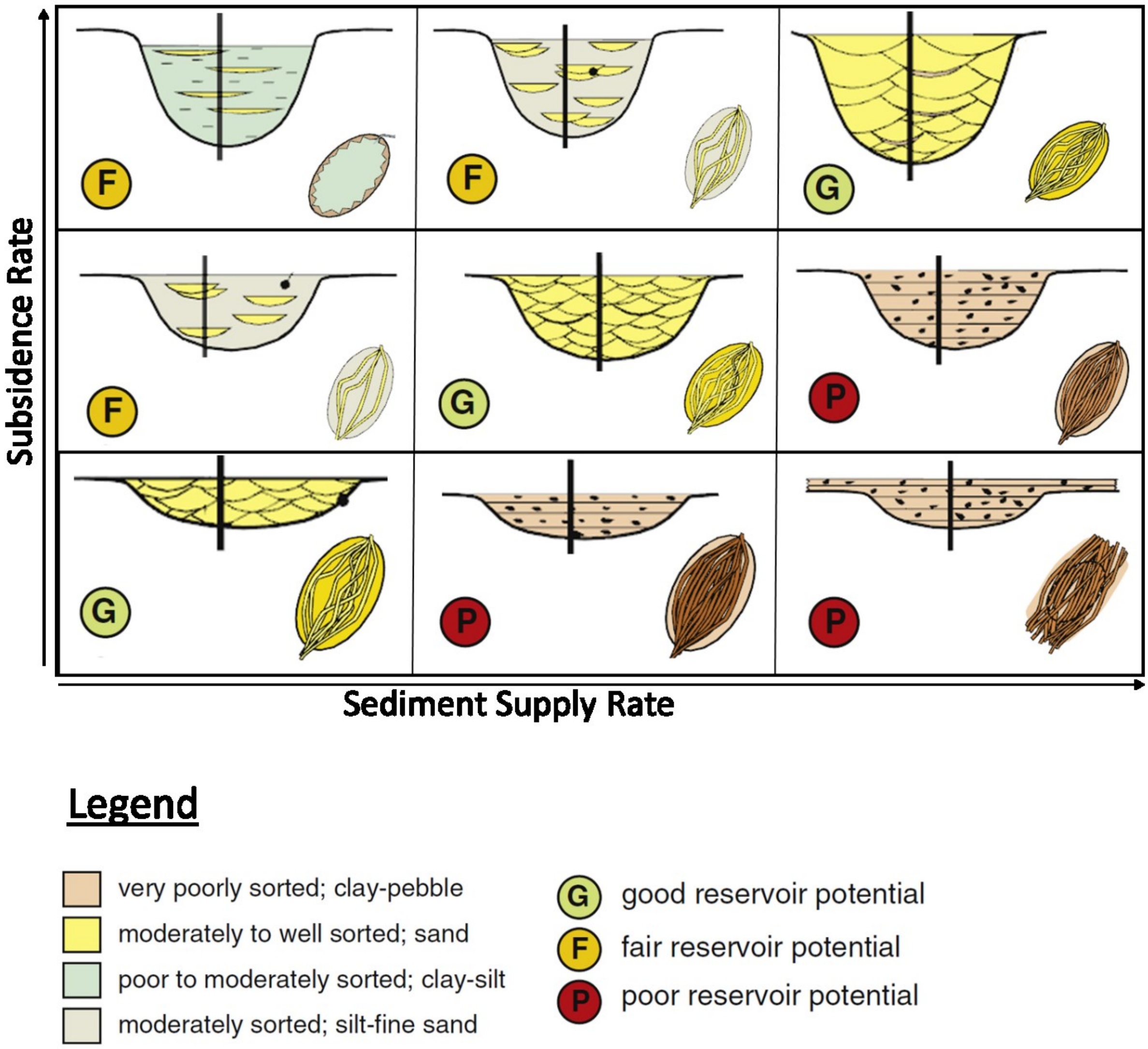


Figure 43: Conceptual model of basin-infill styles and fluvial architecture with interplaying parameters such as sediment supply rate and subsidence rate. Unfilled basins are a result of the subsidence rate outpacing the sediment supply rate, balanced sediment supply and subsidence rate generate a filled basin and an overfilled basin is when the rate of subsidence is outpaced by the sediment supply rate (Modified after Banham and Mountney, 2013b).

E. Ladinian to M. Norian salt mini-basin infill pattern

The overall regional behavior of the fluvio-deltaic systems is described by Klausen (2013) in the Obesum, Norsel, Veveris, Gouvca and Arenaria surveys. The salt-influenced Tiddlybanken and Nordkapp basins are controlled by the regional mechanisms, in addition to the salt tectonics. As a result of evacuation of underlying salt (diapiric growth), these basins experience increased subsidence and accommodation creation. A conceptual model of the mega-sequence architecture is created to illustrate the fluvial channel architecture and the relationship between regressive to transgressive cycles in the Nordkapp and Tiddlybanken basins (Figure 44). This affects the evolution of the basin-infill styles and is illustrated in Figure 45 for Upper and Lower Snadd mega-sequences.

<u>Mega-sequence Lower Snadd: E. Ladinian to Upper Carnian mini-basin sediment-fill</u>

The lower part of the mega-sequence is affected by some diapiric growth in the Tiddlybanken Basin which is dominated by lower delta plain deposits. There is assumed to be isolated channels, with poor connectivity among preserved overbank deposits (figures 42 and 43). As the Northeast sub-basin of the Nordkapp Basin also experiences some salt evacuation it is believed to have the same sediment-infill conditions as Tiddlybanken Basin. Within Study area 2, there is limited subsidence with stable conditions with delta front to coastal plain deposits (Figure 44). The channel infills are interpreted to be anastomosing and meandering. The interval has an early progradational sedimentation pattern in the Tiddlybanken Basin and Northeast sub-basin, with more subsidence than sediment supply influx, leaving the basin to be underfilled (figures 44 and 45).

As the system continued to prograde (upper part of the sequence), the Tiddlybanken Basin experienced salt piercement with the creation of rim-synclines. The Signalhornet Dome was uplifted and controlled the sediment distribution. The systems dominating this interval are upper deltaic plain with channelized fluvial systems. There are no indications of diapiric growth in Study area 2 of the Nordkapp Basin at this time, however large fluvio-deltaic channel systems are prograding across and out of the Nordkapp Basin. These systems are identified inside the basin margin and outside of the Northeast sub-basin of the Nordkapp Basin, and are interpreted to belong to a similar facies association. The Tiddlybanken Basin in Lower Carnian package consists of multistorey channel belts. Study area 2 has several fluvial channel styles, meandering to braided in an upper delta plain environment. This part has channelized systems that show overall thicker sand bodies compared to the Upper Snadd sequence (in the

Tiddlybanken and Nordkapp basins). The 7228/2-1S well logs from this interval are interpreted to be amalgamated and aggradated sand-prone channel-fills. This indicates that the fine-grained systems are rather reworked and removed in the Nordkapp Basin, while well 7228/1-1 on the Bjarmeland Platform has more fine-grained sediments. This supports the theory that the paleo-river channels were more proximal with a wide fluvial drainage system transporting the sediments downstream (to the northwest). This interval is believed to have interconnected to well-connected channel bodies in the mini-basins that are amalgamated and sand-prone. This suggests that the subsidence rate is outpaced by the sediment supply rate in Tiddlybanken and Nordkapp salt basins, and as a result the system continues to prograde and extend. This results in a late progradational to aggradational sedimentation pattern, whereas the basin-fill style is transitioning from a balanced-filled to overfilled basin (illustrated in figures 44 and 45).

The system creates a relatively deep basin in Tiddlybanken Basin, with well-connected channels in a mixture with conglomerate lags at the channel base (Figure 44). The same units identified in well 7131/4-1 show basal channel lags of similar composition. Towards the end of the sequence, the fluvio-deltaic systems begin to retrograde and backstep and are dominated by coastal plain environments. As the subsidence rate outruns the sediment supply delivery rate, it generates an underfilled infill-basin style in the basins (figures 42, 43 and 45).

<u>Mega-sequence Upper Snadd: Lower Carnian to M. Norian mini-basin sediment-fill</u>

The mega-sequence in the Tiddlybanken Basin is dominated by passive (downbuilding) diapirism. In the lower part of the Upper Snadd mega-sequence, the overall fluvio-deltaic systems prograde. Multiple narrow and curved channel-fills are identified in the Tiddlybanken Basin. Due to the activation of the boundary fault in Study area 2 along the Nordkapp Basin (initiated by salt movement) additional accommodation space in the hanging wall has been generated. In this case the subsidence rate and sediment influx rate is balanced. This results in a balanced-basin, which is also expected for Study area 2 and NE Nordkapp Basin (figures 44 and 45). The upper part of the sequence is dominated by transgression and the fluvio-deltaic systems move landward from a lower deltaic to marine in both Tiddlybanken and Nordkapp salt basins. The Tiddlybanken Basin develops a lacustrine environment with feeding deltas located on the margins of the basin and distally located channel-fills are present in Study area 2 of the Nordkapp Basin. This results in an underfilled basin (subsidence rate outpaces the sediment supply rate) (figures 44 and 45).

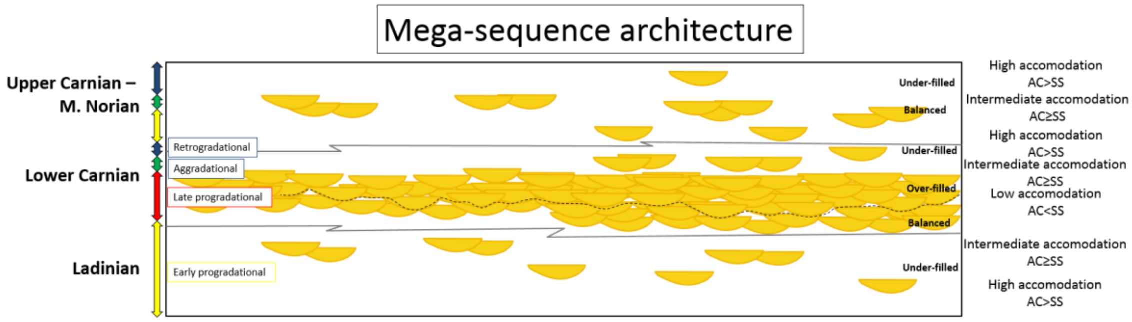


Figure 44: Conceptualized mega-sequence and architecture of the Snadd Formation with respect to progradational and retrogradational segments. The dotted black line illustrates the presence of an expected erosive surface as a result of relative base level fall.

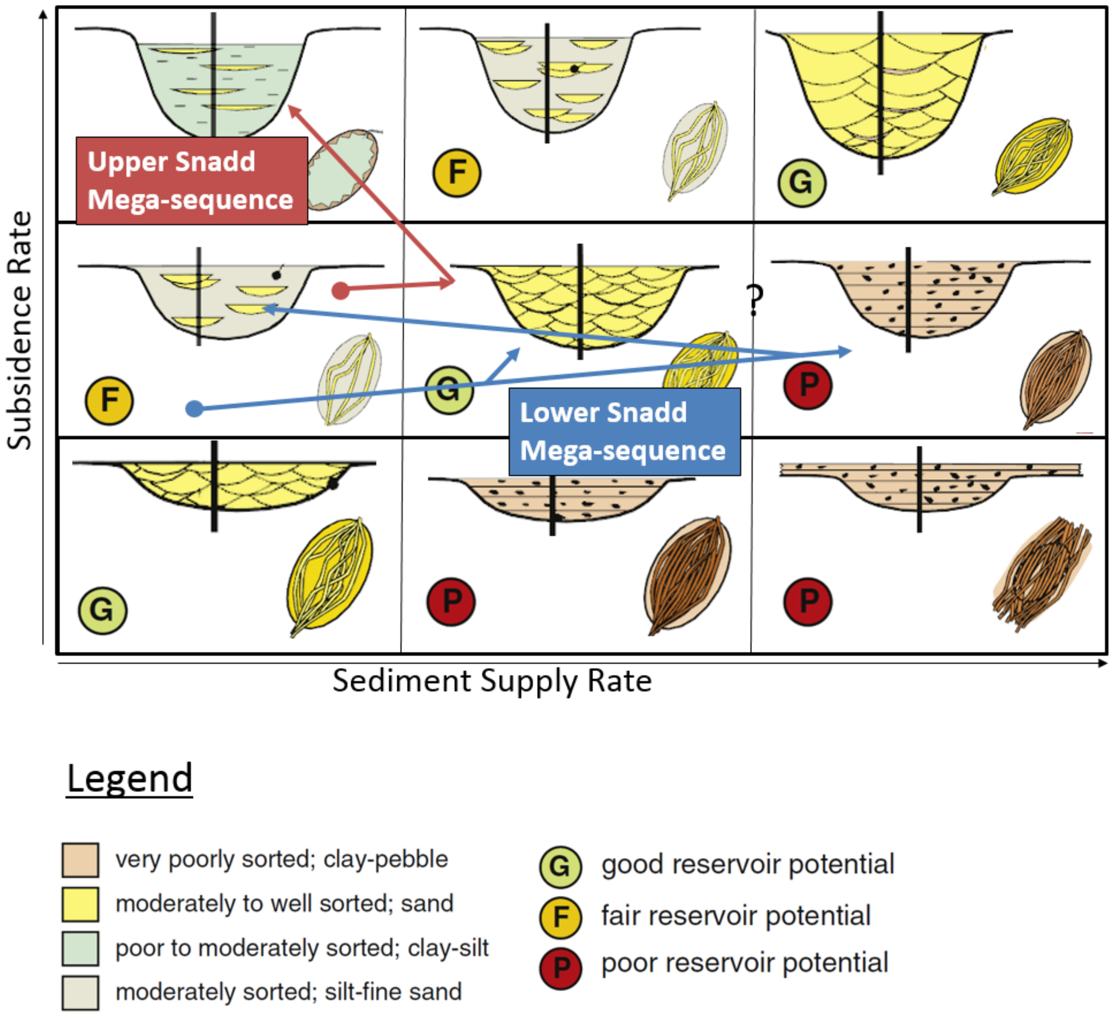


Figure 45: Conceptual model of basin-infill styles and fluvial architecture with interplaying parameters such as sediment supply rate and subsidence rate (Modified after Banham and Mountney, 2013 b). The evolution of the Lower Snadd mega-sequence is indicated in blue and the Upper Snadd mega-sequence in red, and it illustrates the impact of regressive and transgressive cycles on the basin infill style in the two salt basins. The Lower Snadd mega-sequence evolved from an underfilled to balanced and overfilled basin as a result of progradation and as the system started to retrograde the basin became underfilled. The Upper Snadd mega-sequence is affected by the cycles and the evolution of the basin infill style is indicated in the figure.

8.3 Impact of fluvial style and facies architecture on petroleum potential in Tiddlybanken and Nordkapp salt mini-basins

The lower progradational package is dominated by underfilled basin conditions in the Tiddlybanken Basin. The channels are expected to be isolated with poor connectivity distributed between overbank deposits. This lead to a fair reservoir quality, but not optimal. The Nordkapp Basin (in Study area 2) is expected to have relatively similar architecture. The upper progradational unit in Tiddlybanken Basin and Study area 2 is dominantly balanced, but will continue to prograde laterally resulting in an overfilled basin. This package will consist of channel elements that has well developed connectivity between sandy infill to more gravel prone sediments. This is considered to have a great reservoir potential with intermediate to high channel deposit proportion and net-to-gross. As the fluvio-deltaic system starts to retrograde, it creates an isolated and underfilled basin with poor reservoir potential (figures 44 and 45).

The lower part of the Lower Snadd mega-sequence is dominantly underfilled, with some isolated channel fills that has poor connectivity and reservoir potential. The rather isolated channels can act as traps for hydrocarbons in the mini-basins in this interval. The upper part of the Lower Snadd sequence (in the Lower Carnian package) is dominantly a meandering to braided fluvial system with large meanders. It is expected that it is dominantly a braided system with large meanders and has characteristic amalgamated channel-fills associated with good reservoir quality. As fluvial systems are absent on the Signalhorn Dome, it is not expected thief sands in that area. As a result, is likely that there are stratigraphic traps up-dip along the Signalhorn Dome. There is also potential for channels as stratigraphic traps imbedded in the sequence in the mini-basin. The sandstones of Lower Carnian age are found be gas and oil bearing in well 7228/7-1 A (Pandora discovery) (Factpages NPD, 2015). The Upper sequence is considered to have poor reservoir quality, with abundant fine-grained material with deposition of organic-rich sediments in humid conditions. The potentially organic rich-prone lacustrine successions (Tiddlybanken Basin), may charge stratigraphic channel traps embedded in the sequence and the fluvio-deltaic dominated Jurassic succession overlaying the sequence.

9.0 Conclusion

During Triassic, major fluvio-deltaic channel systems dominated the south-southeastern Barents Sea. The Nordkapp and Tiddlybanken basins are examples of salt sedimentary basins with thick successions of Triassic-Middle Jurassic fluvio-deltaic basin infill in the Barents Sea. These large fluvio-deltaic systems were generated as a result of the exposure of the Ural Mountains and Fennoscandia.

The Nordkapp and Tiddlybanken basins formed during Devonian to Carboniferous, with salt deposited in a shallow evaporitic basin during the Late Carboniferous and Early Permian times under the influence of regional extension. Salt growth was initiated in Early-Middle Triassic in the Nordkapp Basin and Middle Triassic in the Tiddlybanken Basin. Several salt mini-basins were formed due to diachronous salt growth in response to differential loading in the Early to Middle Triassic, because of initial progradation of fluvio-deltaic systems. The fluvial stratigraphic architecture and style in the mini-basins is controlled by the interplay between subsidence rate (and subsequent accommodation creation) and sediment delivery rate. The regional scale fluvial systems have its own controlling parameters, but if combined with interplay of active salt tectonics, the areas will be forced to create more subsidence, and resultantly accumulate and stack fluvial systems in mini-basins. As the rate of subsidence rate changes, together with the sediment supply rate, the stratigraphic channel architecture spatially and temporally changes.

The Middle to Upper Triassic Snadd Formation represent two regressive-transgressive fluvio-deltaic mega-sequences systems extending across the entire Barents Sea. These represent two forestepping to backstepping fluvio-deltaic clastic wedges in the Snadd Formation. It is evident by integrating the seismic facies package analysis, amplitude maps, well logs and core data that the systems have experienced phases of progradation, aggradation and retrogradation during the Snadd Formation. Depositional environments range from upper delta plain to marine environments, but are mostly occupied by flood- and delta plain environments with various types of fluvial channel systems. Fluvial styles identified are anastomosing, meandering and braided patterns, however, it is evident from the present study that the down-stream systems are more mixed. It is suggested a fluvial style more towards a braided channel systems with large meanders in the Lower Carnian package. Additionally, the fluvio-deltaic systems have a difference in fluvial character and style in the mini-basins compared to the systems on the stable platforms. Downstream change in fluvial style illustrated from the analogue modern Irrawaddy River (Myanmar) demonstrate the expected east-west changes in fluvial channel systems identified through the Snadd Formation; these represent a change from a proximal to a distal part of the downstream system.

The salt diapirism interaction with the fluvio-deltaic systems has generated rim-synclines along the salt walls with large fluvial systems captured by the rim-synclines, resulting in fill-spill infill pattern of the salt mini-basins. In the lower progradational and retrogradational packages, the dominant fluvial character is meandering to anastomosing, with underfilled conditions in the salt mini-basins. The middle part is a succession with balanced to overfilled basin conditions with vertically stacked channel fills with broad meandering to braided systems/channel complexes. The upper part is dominantly balanced to underfilled, with meandering and anastomosing fluvial styles, with an development of lacustrine environment. In Early Carnian time, Tiddlybanken Basin experienced increased diapiric growth and with high rates of sediment influx; the mini-basin was dominated by balanced to overfilled basin infill style. The same fluvio-deltaic systems are expected to extend across the Finnmark Platform, entering and exiting the Nordkapp Basin to the Bjarmeland Platform. Furthermore, the salt structures (i.e. salt pillows underneath the Signalhorn Dome) control the sediment distribution in the mini-basin. Due to the salt walls, pillow and diapirs, the channelized systems will migrate alongside these topographic highs.

It is expected that the channel fills are vertically stacked in the mini-basins compared to tge presence of lateral accretion on platforms. With a greater net-to-gross and channel proportion in the middle part of the Snadd Formation, it is expected to have a good to excellent reservoir quality potential. The dominantly fine-grained under and overlaying parts, seal potential stratigraphic traps such as fluvial channels in the mini-basin and/or updip along a structure. Organic rich deposits are expected within the lacustrine environment, which has the opportunity to act as a potential source rock for the embedded channels or overlaying Jurassic strata. The vertically stacked channel fills as identified in the Lower Carnian is expected to be well-connected in comparison with the platform packages of lateral accretion and the under-filled parts in the mini-basins.

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