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Salt Controlled Fluvial Systems in the Norwegian Danish Basin, Central North Sea; The Impact on Triassic Petroleum Prospectivity

by

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ABSTRACT

The Norwegian Danish Basin is situated in the intracratonic Central North Sea. During Triassic the basin filled with thick units of syn halokinetic arid to dryland fluvial successions of the Smith Bank Formation and the Skagerrak Formation. The aim of the present study is to asses the influence of syn-depositional halokinesis on the fluvial reservoirs in order to investigate the play potential of Triassic Strata in the basin. The regional mapping and interpretations were executed using a grid of different 2D seismic surveys covering the Central North Sea area. Well data and core interpretations were applied to support lithology calibrations of to the Triassic units.

The Triassic succession was subdivided into two megasequences, the Lower Triassic Unit T1 and the Upper Triassic Unit T2. Lower Triassic Unit T1 comprises massive floodplain and playa deposits with interbedded pluvial sheet floods. The Upper Triassic Unit T2, on the other hand, comprise stacked fluvial packages were stratal architecture changes and lateral extent increases upwards.

The basin is situated on a Late Permian graben system infilled by thick Zechstein evaporites. Halokinesis was initially triggered by extension and differential loading. The initial to early basin structuring was locally restricted to the Egersund Basin area, whereas the subsequent main Middle Triassic basin-wide halokinetic structuring was located in the central parts of the basin. The final post-Triassic salt evacuation and trap-formation for the Triassic succession were related to basin margin collapse.

Potential Triassic hydrocarbons are situated in fluvial reservoirs located in structural and stratigraphic traps The traps are related to supra salt deformation or fluvial architecture pinch outs in rim synclines. A thick claystone package between the two seismic units forms the seal to Lower Triassic Unit T1 reservoir. Upper Triassic Unit T2 reservoirs are connected to Jurassic reservoirs of the Vestland Group. Hydrocarbon migrations are suggested to be from the Jurassic source rocks situated in the Central Graben or from underlying Paleozoic source rocks in the Norwegian Danish Basin.

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1 INTRODUCTION

1.1 Rationale

This thesis addresses components of the play characterization and potential of the Triassic succession within the eastern Central North Sea basin (fig. 1-1). The study area encompasses the south-western part of the Norwegian-Danish Basin, the Sørvestlandet High and the eastern part of the Central Graben (the Steinbitt Terrace) as demonstrated in figure 1-1. The Triassic strata in this area form a thick succession preserved within 'pods' between salt walls and diapirs/stocks composed Permian Zechstein evaporates (Goldsmith, Hudson, & Van Veen, 2003)

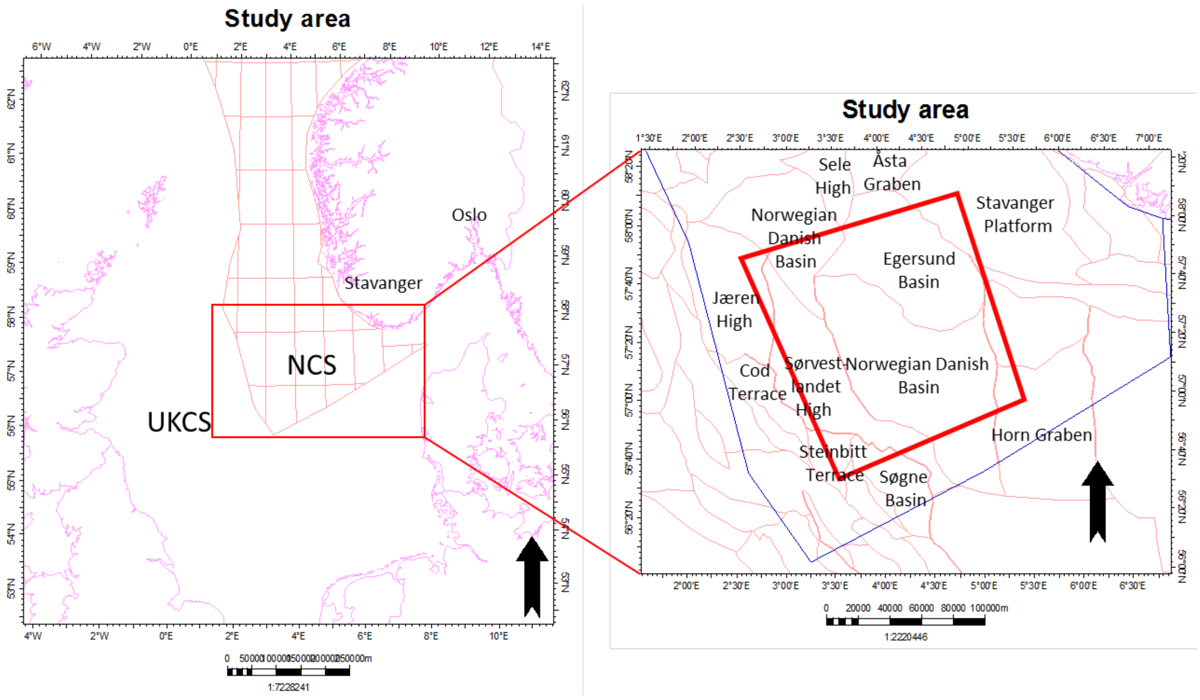


Figure 1-1 Location of the study area located in the Central North Sea (CNS). The study area is marked by the red square on the figure on the right that includes the structural basins comprised in the study area.

Exploration of the Triassic in the Norwegian part of the Central North Sea is proven challenging with only a few but noticeable discoveries along the eastern Central Graben area, such as underneath the Upper Jurassic Ula Field reservoir ((NPD), 2019c). Recently hydrocarbons have also been encountered in the Triassic in the Oda Field on the Sørvestlandet High (Ravnås 2019, personal communication), proving the extension of the Triassic play out of the Central Graben. This is in contrast to the more successful exploration of the Triassic succession along the western and central parts of the Central Graben (Goldsmith et al., 2003). Hydrocarbons in the Triassic are encountered in salt-related traps, within fluvial reservoirs of the Skagerrak Formation (Kape, Diaz De Souza, Bushnaq, Hayes, & Turner, 2010). Although reservoir age appears to vary both between fields and other tested structures. In consort, this suggests a relatively complex structuring and basin infill story also during the Triassic which is essential to understand to further explore for the Triassic potential within the Norwegian part of the Central North Sea.

The main focus of this thesis is to further evolve our understanding of the initial and early Triassic halokinetic structuring of the eastern part of the Central North Sea and how this impacted the resultant basin infill style, especially with respect to the outbuilding and retreat of basin marginal fluvial clastic wedges (McKie, 2014). The aim is to decipher early structuring and how this influenced the subsequent structural-halokinetic evolution, structural domains and thus play segments. Secondly how this can be further utilized to predict reservoir fairways, types and quality within the basin, and thereby reservoir segments within the area. Finally, an attempt will be made to partition the Triassic succession into reservoir prone, reservoir lean or barren intervals based on seismic character, thereby allowing identification of areas with stacked reservoirs separated by thick and extensive seal intervals, i.e. the seismic character to allow identification of individual Reservoir-Seal Pairs within the basin.

1.1.1 Area Challenge

Exploration in the Norwegian parts of the Central North Sea started already with the opening of the Norwegian Continental Shelf for petroleum activities in the 1960'ies (Evans et al., 2003). The Sørvestlandet High and Norwegian-Danish Basin have accordingly been subject to prolonged exploration activity. Only a few wells with deeper, Paleozoic targets have drilled a full or near complete Triassic succession (Goldsmith et al., 2003). Hence deeper, Triassic and Palaeozoic stratigraphy, remain poorly calibrated within the basin.

Early drilling rapidly established that the common North Sea Upper Jurassic source rocks were immature to only locally marginally mature in the Norwegian-Danish Basin, except for within the deeper sub-basins (Husmo et al., 2002). The bulk of study area, i.e. Sørvestlandet High and the south-western part of the Norwegian-Danish Basin, traditionally have been challenged on charge or migration efficiency, rendering the perception of the area as non-prospective and as a 'Dry hole belt'(Bjørnseth & Gulyas, 1995; Karlo, Van Buchem, Moen, & Milroy, 2014). This perception was challenged with Paleocene discoveries along the so-called Siri trend (Paleocene 'Siri-fairway') along the Norwegian-Danish border which proved long-distance lateral migration out of the Central Graben hydrocarbon kitchen area (Hamberg, Dam, Wilhelmson,

& Ottesen, 2005). The hydrocarbon-bearing Triassic-Jurassic in the Oda Field proves that longer distance migration also can occur in the deeper strata, analogous to what is also proven on the Utsira High and the discovery of the Johan Sverdrup away from the hydrocarbon kitchen area to the north of the study area ((NPD), 2019b). Mapping of reservoir fairways across the Norwegian-Danish Basin and into the Central Graben is critical to further constrain potential migration routes out of the hydrocarbon kitchen to establish prospective hydrocarbon provinces in the basin margins.

1.1.2 Data Challenge

Interpretation and analysis of the Triassic succession in the Norwegian Danish Basin and on the Sørvestlandet High have historically been hampered by relatively low resolution vintage 2D seismic data with limited well calibration (Goldsmith et al., 2003). Only over the recent years, have newer regional 2D seismic surveys with improved seismic quality become available. Repeated acquisition over several years has produced a fairly dense grid (see chapter 4). The dense grid allows consistent and coherent regional mapping of the Triassic succession across the basin. The dense grid also allows to detail out the seismic facies variability and correlation within individual salt defined minibasins.

Modern 2D seismic data allow for subdivision of the Triassic succession into two seismic units or megasequences that broadly correlates with the Lower-Middle and Upper Triassic. However, the lack of regionally extensive seismic markers makes it challenging to apply reliable regional interpretation within the two identified Triassic megasequences (see also Goldsmith et al. (2003)). In addition, modern, laterally extensive broadband 3D data have been acquired to cover large swatch across parts of the study area. The arrival of high-quality 3D data provide the opportunity to apply detailed seismic facies interpretation and inferred depositional system distribution within individual salt minibasins. With well control this approach can be exported to adjacent non-calibrated minibasins. Accordingly, improved calibration and lithology precisions should be achievable for parts of the study area.

Upgraded biostratigraphical resolution of the perceived 'fossiliferous barren' Triassic strata has been achieved by improved palynology framework that can be applied across the Central North Sea (Goldsmith et al., 2003; Greig, Hartley, Gray, & Burgess, 2017; Preston et al., 2002). This has enriched regional correlation, which coupled with provenance data/chemostratigraphy, has supported the presence of multiple delivery systems from both sides of the basin margin (McKie, 2014, 2017). Combined with new well data acquired over the last 10 + years it is now time to generate a more thorough and reliable mapping of the Triassic succession also over the eastern Central North Sea (Goldsmith et al., 2003).

1.1.3 Geology Challenge

The geological challenges within the study area are numerous. Exploration and mapping of the North Sea geology have at times been constrained to its political boundaries and not as a complete basin, this has resulted in limitations to the understand the full basin evolution within the area (Lervik, 2006).

The main challenges related to the spatial and temporal evolution of this part of the Central North Sea Basin with relation to timing and style of initial salt structuring and the subsequent Triassic halokinetic evolution. Structural domains, such as the ones created by Gulyaeva (2016) are hard to define as the structural style of the salt is quite different and to some degree randomly distributed in the North Sea. She defined them based on the structure style and orientation as seen on the domain map from figure 1-1. Salt tectonic domain 1 and 2 coincide with the study area of this thesis.

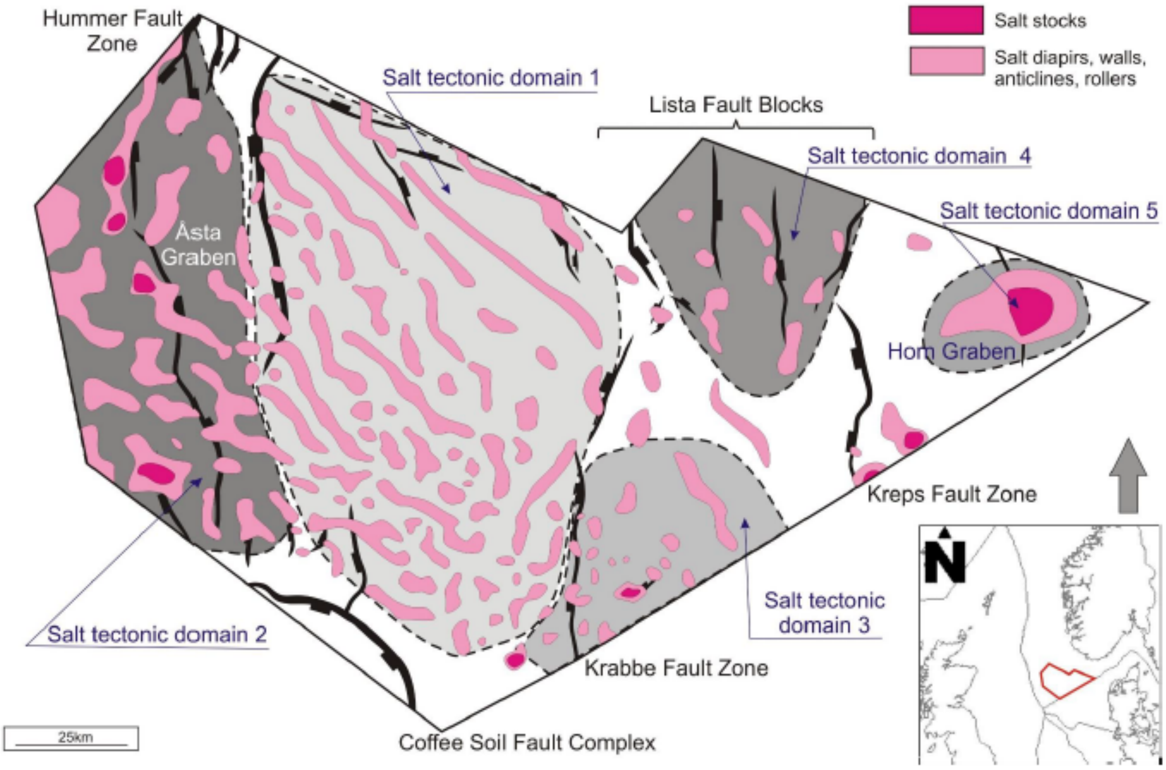


Figure 1-2 Salt tectonic domains of the Norwegian Danish Basin based on structural style and orientation of salt structures (Gulyaeva, 2016).

Fossen (2010) describes different salt structures and the term diapir describe the structures that pierce the overburden whereas pillows and anticlines are bending the overburden rocks. Further, he states that they are either elongated shapes such as salt walls or rounded features such as salt stocks. The different salt structure types are seen in figure 1-3, from figure 1-2 the most common structure in the study area are salt walls.

The onset and evolution of Zechstein Salt structures are poorly understood, and several tectonic pulses have deformed the Zechstein Group salt deposits in the central North Sea (Coward, Dewey, Mange, Hemption, & Holroyd, 2003). There may be no link between the present day structures and initial structural style of the Zechstein salt due to the tectonic pulses. Different models have been suggested for the salt structuring in the North Sea, where also supra salt minibasins are formed situated on top of salt walls. Mannie, Jackson, and Hampson (2014a) summarises three different models for supra salt pods, the first model by collapsing salt walls was proposed by Hodgson, Farnsworth and Fraser (1992), Penge, Munns, Taylor, and Windle (1999) suggests extensional grabens, whereas the salt dissolution model was created by Clark, Cartwright, and Stewart (1999) (fig 2-3). The models will be further discussed in chapter 2. Different preservation of potential Triassic deposits is observed in the pods vs. interpods. Older Triassic strata are often penetrated in the interpods whereas the younger Triassic is drilled on the pods where the full sequence rarely is penetrated (Karlo et al., 2014).

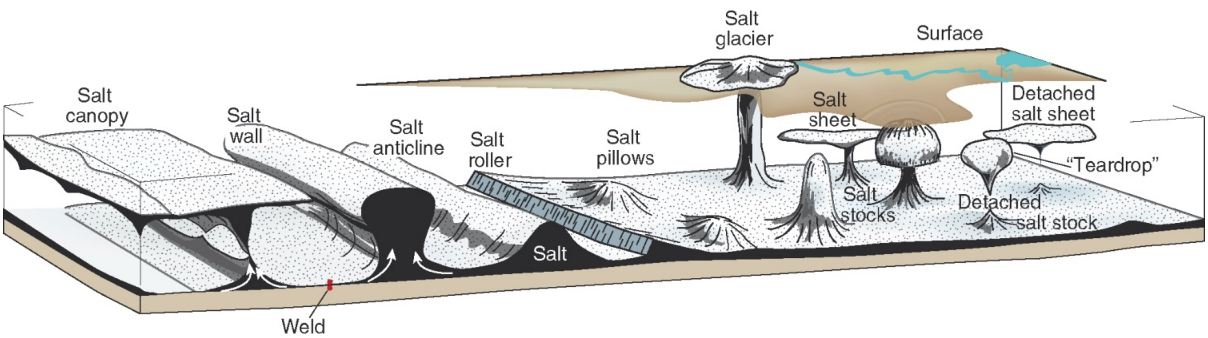


Figure 1-3 Common salt structures formed by halokinetic movement (Fossen, 2010). Salt walls and salt stocks are common features in the study area.

The Triassic succession is widely distributed and comprises thick packages deposited in salt pods. The two fluvial megasequences are stratigraphically changing from an arid environment to a dryland setting (McKie, 2014). Triassic is characterized by red-bed strata and hence have a very monotonous lithology and seismic expression; this creates few seismic markers on a regional scale and makes it challenging to map out (Goldsmith et al., 2003). Although seismic markers are present, they are restricted within pods making the residual exploration and mapping challenging (see chapter 5.2). The intra Triassic markers are also differentially distributed; some sedimentary pods comprise several reflector packages to divide the succession, whereas other pods have non-visible markers (Jarsve et al., 2014). The marker has been referred to as deposits of marine, lacustrine or carbonate processes (McKie, 2017). Well and core control is sparse and there is little to no calibration of the lithology of the succession, especially within the Lower Triassic megasequence (see chapter 4,5 and 6). Fluvial systems change their appearance areally impacting the depositional style over the area from proximal to distal expressing differences in the seismic expression (McKie, 2014)

Early Jurassic uplift resulted in erosion of the uppermost parts of the Upper Triassic (Goldsmith et al., 2003; Husmo et al., 2002). Post mid-Jurassic structural evolution and modification of Triassic structural style makes it challenging to restore the Triassic structural style, but it has been attempted by studying internal pod geometries and terminations of Triassic strata in a 3D point of view (Karlo et al., 2014; Scheck, Bayer, & Lewerenz, 2003).

1.1.4 Triassic plays in the Central North Sea

Only five percent of the petroleum discoveries and producing fields in the central and northern North Sea is located within the Triassic succession (Goldsmith et al., 2003). Examples of Triassic hydrocarbon accumulation on the UKCS are seen in figure 1-4. The figure shows the tectonic pulse, timing and reservoir formation coinciding with the field development.

1.1.4.1 Source Rock

The common source rock for Central and Northern North Sea Triassic discoveries and fields are the Upper Jurassic Mandal and Farsund Formation (Fraser et al., 2003; Knight, Allen, Copiel, Jacobs, & Scanlan, 1993). Additionally, the Upper Permian Stinkkalk carbonate shale of the Zechstein Group is a proven source outside the North Sea in German and Polish onshore fields (Geluk, 2005). Also, the Upper Permian Kupferschiefer locally constitute a source rock in the onshore Netherlands which may be the equivalent of a proven non-commercial source on the Mid North Sea High (Jackson & Stewart, 2017).

1.1.4.2 Reservoir

Reservoirs are situated in Triassic red-beds, mostly fluvial channel deposits from the Smith Bank Formation, thicker fluvial intervals of the Skagerrak Formation, and fluvial to marginal marine sandstones of the Gassum Formation (Fisher & Mudge, 2009). In the central North Sea

Basin, the fluvial strata range from an arid type in the Lower to Middle Triassic associated with probable aeolian reservoirs, to semiarid or dryland fluvial strata in the Upper Triassic (Goldsmith et al., 2003). In the uppermost Triassic, the fluvial reservoir units become more humid in nature. The controlling factors on the reservoir quality are compaction, facies distribution, diagenesis and temperature controlled cementation based on empirical analysis across the Central Graben (Grant, Middleton, & Archer, 2014).

1.1.4.3 Seal

The top seal is provided by Lower or Middle/Upper Jurassic claystone of the Fjerritslev and Tyne Group respectively. Where the Vestland Group overlies the Triassic, there routinely is vertical connectivity between the two play types. Intraformational seals are provided by thicker intervals of Triassic claystones, either of floodplain, lacustrine or potential marginal marine origin. The latter is locally interbedded with thin carbonate stringers, especially within the Middle Triassic interval that separated the two seismically defined Triassic Megasequences (Karlo et al., 2014; McKie, 2014). Base seal and side seal are provided by the Zechstein salt (Jackson & Stewart, 2017).

1.1.4.4 Trap

As salt generates diapirs the overburden is destroyed resulting in rim synclines flanking the diapir generating perfect potential traps (Glennie, Higham, & Stemmerik, 2003). Salt walls are trending north-south situated in respect to underlying reactivated Permian faults (Hodgson et al., 1992). The Judy Field on the UKCS is located in halokinetic induced horst and is highly faulted, whereas the Beryl and Nevis field on the UKCS and Snorre field on the NCS are positioned in tilted fault blocks (Goldsmith et al., 2003). (Gulyaeva, 2016) summarized the common supra salt traps in the Norwegian Danish Basin to include both structural (halokinetic induced anticlines and faults) and stratigraphic traps (turtle structure anticlines, pinch-outs and facies change).

1.1.4.5 Field Examples

On the Norwegian Continental Shelf, a few numbers of fields produce from Triassic reservoirs. Located in the Northern North Sea are the Snorre, Visund and Ivar Aasen fields and in the Central North Sea field examples of fields are Gunge, Sigyn, Gaupe and Ula ((NPD), 2019e). On the UK sector, there have been better Triassic exploration success and example of producing field are the Beryl and Nevis fields on the southern part, west of the Viking Graben and the Judy field located on the Josephine ridge in the southern Central Graben (Goldsmith et al., 2003). In the Heron Cluster on the UK sector, the main reservoir is the Triassic Skagerrak formation (fig 1-4) (McKie & Audretsch, 2005).

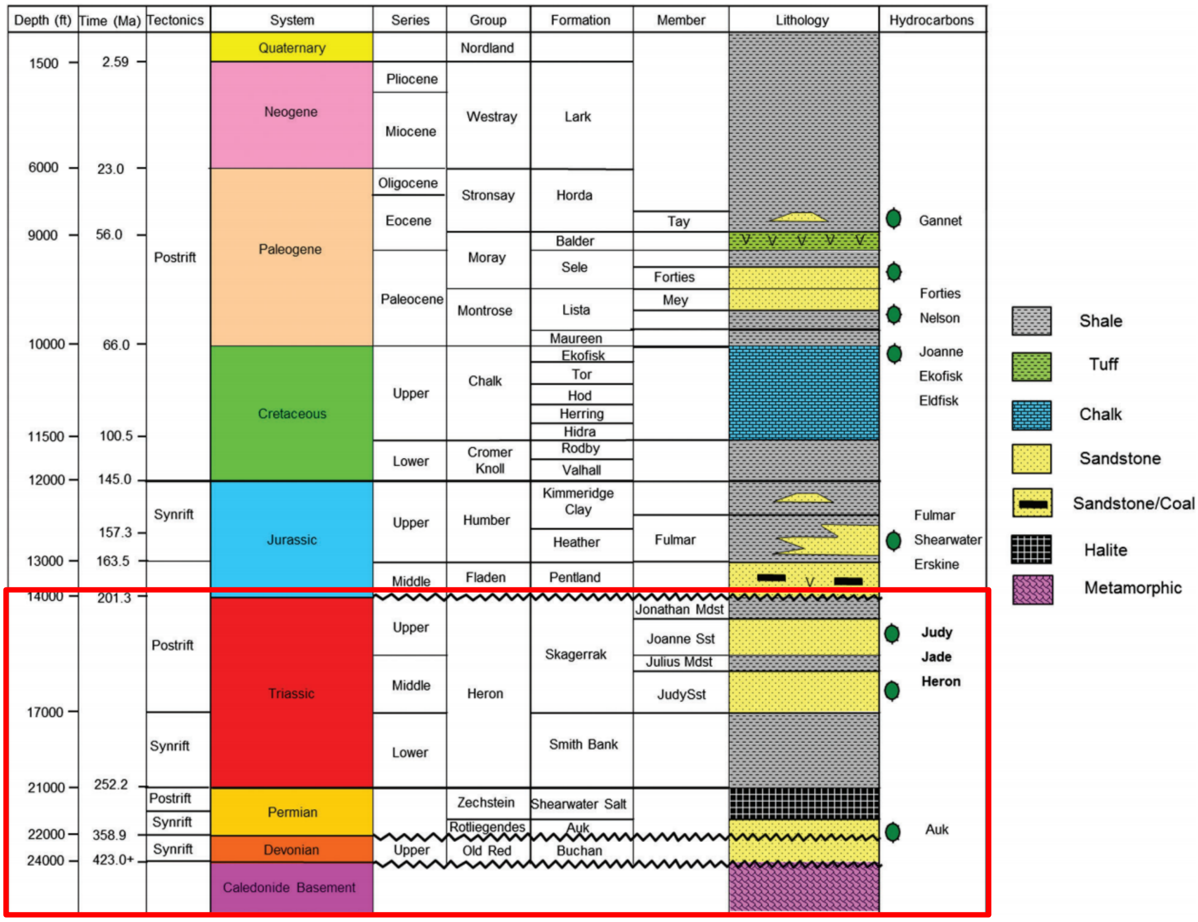


Figure 1-4 Central Graben regional stratigraphy, tectonic pulse and hydrocarbon accumulations on the UKCS, the red square summarizes the potential elements for a Triassic play model (Grant et al., 2014)

1.2 Aim and Objectives

The aim of the study is to determine the influence of syn-depositional halokinesis on dryland fluvial reservoirs in order to investigate the play potential of Triassic Strata in the Central North Sea. To fulfill the aim of the research the main objectives are

- Identify diagnostic criteria to differentiate Triassic structural provinces.
- Identify and evaluate different depositional Triassic provinces.
- Differentiate fluvial stratigraphy and potential reservoir types.
- Asses the Triassic play potential in the salt influenced Norwegian Danish Basin.

The objectives will be done from a combines structural and stratigraphic approach.

2 THEORETICAL BACKGROUND

2.1 Basin Type

The North Sea Basin is presently an intracratonic basin formed on top of a failed rift system (Busby & Ingersoll, 1995). During the Late Permian to Late Jurassic, the basin formed an active rift entering into a post-rift stage during the Early Cretaceous with a gradual change into the current intracratonic basin style (Zanella & Coward, 2003).

During most of the Triassic, the North Sea basins essentially transformed into a post-rift state following the Late Permian to Early Triassic rift episode (fig. 1-4) (Grant et al., 2014). During the Middle to Late Triassic, the North Sea basins were continental and influence by discontinuous rifting (Goldsmith et al., 2003). The Late Early Triassic to Late Triassic basin evolution can be classified as representing an inter-rift period (Ravnås, Nøttvedt, Steel, & Windelstad, 2000). The presence of thick Permian salt that already in the Early Triassic started to form incipient salt structures, defines the Central North Sea as a salt influenced inter-rift basin with growth of salt structures controlling position and types of sub-basins during the Triassic (Zanella & Coward, 2003).

In adjacent basins e.g. the Northern North Sea, Permian rifting, prevailed at least until the Early Triassic (P.J Goldsmith et al., 2003; Ravnås et al., 2000). By analogy, it is not unrealistic to assume that active rifting may have dominated during the Early Triassic also in the Central (and Southern) North Sea. The Lower Triassic within the study area may accordingly represent the latter part of a syn-rift episode, the fact that typical syn-rift infill geometries are not observed may be attributed to halokinesis during this stage of rift basin development (fig.1-4 and fig. 2-1). In turn, this may favour reactive salt structuring, probably genetically linked to active extensional structures, as the main initial structural style (see chapter 6)(Jackson & Tablot, 1986).

2.2 Late Syn-Rift to Post-Rift Basin Development and Infill Architecture

2.2.1 Structural Framework & Basin Architecture

Active intra-continental extension creates syn-rift basins with a half – or full graben topography, commonly with deeper basins along the central part of the rift and less pronounced basin topography towards the rift margins (Withjack, Schlische, & Olsen, 2002). This is observed at top Rotliegend (pre to syn-rift transition for the Permo-Triassic basin fill) in cross sections across the Central North Sea (figure 2-1). Triassic basin formation should accordingly be viewed as both syn-rift (Early Triassic), albeit representing the later part of a prolonged rift episode, with a transition into a prolonged post-rift or inter-rift stage (Middle to Late Triassic) (Coward et al., 2003; Ravnås et al., 2000).

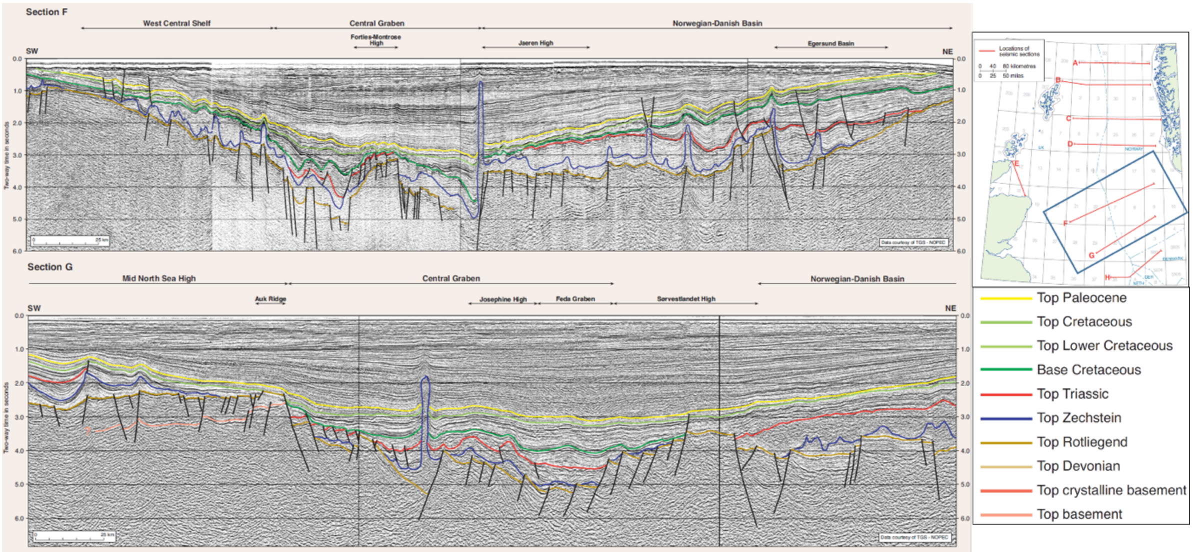


Figure 2-1 Regional cross sections of the Central North Sea. The horizons correspond to geological ages (Zanella & Coward, 2003).

Active extension is normally associated with significant basinal subsidence, where extension rate and subsidence is higher over the central part of the rift basin, tapering away towards the rift margin (Gawthorpe & Leeder, 2000). The localized presence of the Lower Triassic strata suggests that an early Triassic extension involved the formation of a series of salt controlled sub-basins (Hodgson et al., 1992). The early Triassic rift basins likely formed a complex array of subsiding sub-basins, which likely changed shape and geometry as rifting and halokinesis continued (Banham & Mountney, 2013; Karlo et al., 2014).

The inter-rift stage (Ravnås et al., 2000) of the Middle Triassic-Middle Jurassic North Sea basins was characterized by overall high subsidence rates, repeatedly enhanced by intermediate minor rifting events. A similar evolution is also proposed for the Triassic Norwegian-Danish Basin, where sporadic Middle Triassic rifting produced noticeable changes in basin geometries and likely enhanced subsidence rates (Goldsmith et al., 2003). The Triassic of the study area accordingly is argued to represent an interval of high but temporarily variable subsidence rates, allowing in turn, for continuous high (but variable) rates of accommodation creation (Goldsmith, Rich, & Standring, 1995).

During the Middle to Late Triassic, salt structuring prevailed, but now likely in the form of active gravitational driven halokinesis (see section 2.2.2), in turn related to sediment loading from the continuously accumulating Triassic succession (Coward et al., 2003). The change from inferred Early Triassic reactive to Middle to Late Triassic active halokinesis appears to have been associated in change with salt-controlled minibasins geometries, reflecting changing types of salt structuring as the basin evolved (see chapter 5)(Karlo et al., 2014). Salt withdrawal furthermore enhanced subsidence within the salt controlled sub-basins, thereby adding to the already high rates of accommodation creation within these basins (Hodgson et al., 1992; Peel, 2014)

2.2.2 Salt Structuring of the Study Area

Salt is not similar to other sedimentary rocks, it does not compact during burial, have lower density than the overlying deposits, act as a viscoelastic medium under most geological processes and flow as a Poiseuille flow generating diapirs (Fossen, 2010). Salt does not move on its own and require forces to contribute and initiate the movement and generating of diapirs. The forces triggering salt movement are gravitational loading from sediment influx, tectonic loading in response to a regional extension or compression and thermal loading as salt volume increases when salt is heated (Martin P.A. Jackson & Hudec, 2017a). As salt move as a Poiseuille flow, it deforms the overburden strata crossing geological time boundaries. This is demonstrated in figure 2-2 and the cross sections in figure 2-1.

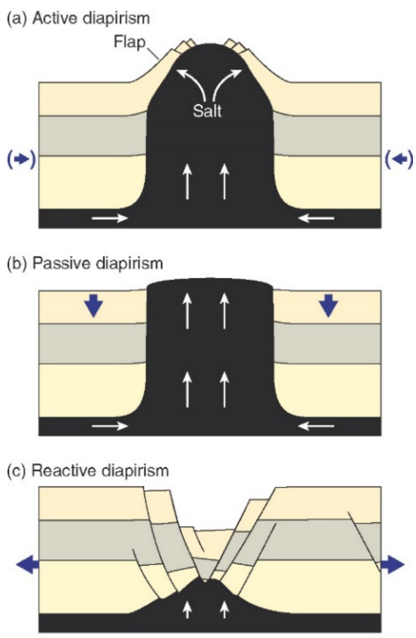


Figure 2-2 conceptualized figure of the different salt diapirism processes (Fossen, 2010)

The three main types of salt diapirism processes in a basin during extensional tectonics are active, passive and reactive diapirism (fig. 2-2). The process of active diapirism commences with an external force such as extensional tectonics (see the section above). During active diapirism, overlying rocks are pushed aside generating large upturned flaps in respect to the salt diapir (Fossen, 2010). As the diapir pierces the overburden it flows independent of regional extension and is then controlled by the thickness and density of overburden and geometry and size of the diapir (Vendeville & Jackson, 1992). Passive diapirism is characterized as when the salt has pierced the overburden and emerge at the surface (Harding & Huuse, 2015). Passive diapirism is also termed down building as the process occurs at the same time as sediments are deposited in the adjacent basins (Jackson & Hudec, 2017b). The passive diapirs still grow as sediments around are deposited until the minibasins ground. The stratal expression is defined by symmetrical deposits where features such as pinch-outs, thinning and upturning are locally situated in the proximity of salt flanks (Quirk & Pilcher, 2012). Reactive diapirism occurs in response to extensional tectonics and terminates when the extension ceases (Fossen, 2010). As the main controlling factor is the extension, the process generates triangular shaped salt walls and can have both symmetric and asymmetric appearance (Jackson & Hudec, 2017b).

A less common structure within the Triassic deposits in the Central North Sea strata is turtle structures. Turtle structures form when the underlying salt is fully evacuated beneath and local highs are generated (Karlo et al., 2014). When the turtle structures generates, the relationship between the underlying synform and the overlying anticline is shifted downward deforming the basin fill (Peel, 2014). Vendeville and Jackson (1992) summarized two types of turtle structures, the first type is generated as salt pillows collapse and generate adjacent diapirs and the second type is generated by extension of overburden generating a horst.

Supra salt minibasins or inter-pods are common for the Central North Sea, especially on the areas on or close to the Central Graben (Karlo et al., 2014). Supra salt minibasins formed on salt walls adjacent to grounded pods, when the pods ground the feeding of salt to salt walls terminated resulting in salt wall collapse (Smith, Hodgson, & Fulton, 1993). Three models have been generated to explain the salt wall collapse and supra salt minibasin formation. The models are shown in figure 2-3 and are the pod-interpod model, the rift-raft model and the salt dissolution model (Mannie et al., 2014a).

The pod- interpod was suggested by Hodgson et al. (1992) and explains the supra salt minibasins to occur as salt walls collapse after salt withdrawal finishes due to grounding of pods. The model argues that Early Triassic base salt extension and deposition resulted in passive diapirism in combination with dissolution of surfaced salt in the Central North Sea followed by Jurassic extension and supra salt basin formation (Mannie et al., 2014a). The rift-raft model was proposed by Penge, Taylor, Huckerby, and Munns (1993). They discuss their rift-raft model where the rafts are thick undeformed Triassic strata separated by localized grabens from a regional extension causing passive halokinesis deformation. The regional extension caused down dip gravity gliding of Triassic deposits overlying a salt detachment layer (Penge et al., 1999). The most significant difference between the two models are the localization and timing of initiation of salt structuring (Goldsmith et al., 2003). The final model is the salt dissolution model by (Clark et al., 1999), which discuss the salt dissolution on the West Central Shelf in the Central North Sea. The model focus on the creation of Triassic sinkholes due to Early Triassic karstification of the Zechstein Evaporates generating collapse features on the salt walls (Clark et al., 1999; Mannie et al., 2014a).

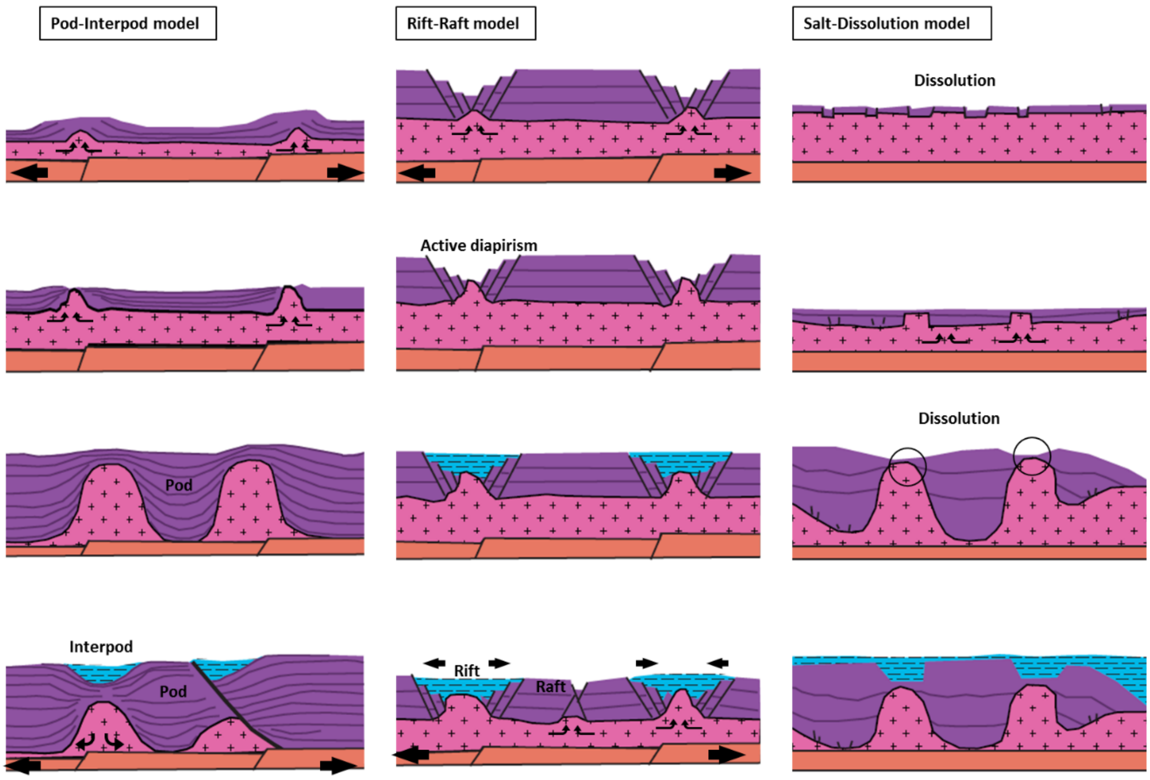


Figure 2-3 Salt evolution models based on Hodgson et al, Penge et al and Clark et al modified after Mannie et al. (2014a). The different models explain the potential formation of supra salt mini-basins.

The common salt structure within the Norwegian Danish Basin east and the West Central Shelf area is the collapsed anticline diapir, whereas supra salt minibasins are more common for the Central Graben area (Karlo et al., 2014). The collapsed anticlines form when the layer above the anticline is thinned due to an extension or by erosion of high amplitude folds, when failure of the overlying deposits occur the salt evacuates into diapirs (Stewart & Coward, 1995)

2.2.3 Basin-Fill

Hodgson et al. (1992) state that Permo-Triassic rifting initiated halokinesis and created basins for Triassic sediments, whilst deposition enhanced the subsidence and eventually transformed these to 'pods' as salt was evacuated into diapirs, eventually the pods grounded. Triassic basin fill and sediment dispersal were from longitudinal or axial fluvial streams derived from hinterlands and marginal alluvial fan deposits (Goldsmith et al., 2003). McKie (2014) argues that Triassic basin formation and infill was intimately controlled by the interplay of intermittent regional extension, climate and halokinesis. He further states that movement affected the Early Triassic Smith Bank Formation deposition more than the overlying Skagerrak Formation in the central North Sea.

In both the northern and central North Sea there is a proximal to distal fining of the fluvial deposits representing proximal to distal facies tracts and fluvial to floodplain subenvironments (McKie, 2014). The overall coarsening upwards structure of the Triassic succession are accordingly interpreted to represent an overall outbuilding of the fluvial system to also occupy the central parts of the basin during the late Triassic (Goldsmith et al., 2003). The two formations constituting the main Triassic succession in the Central North Sea are the fluvial to lacustrine Smith Bank Formation and the terminal fluvial Skagerrak Formation (fig. 1-4).

2.2.4 Sediment Supply

Goldsmith et al. (2003) argue that the Triassic sediment supply is variable and in balance with the accommodation creation as a result of the episodic rifting and the lack of flooding during the time period. Temporal and spatial variation in sediment supply resulted from the combined effects of local depositional environment and climate, tectonics and halokinesis.
Based on paleocurrent data and provenance studies McKie (2014) states that the fluvial systems in the North Sea were derived from both the UK and the Fennoscandia margins.

2.2.5 Accommodation Space & Creation

The Triassic deposition was mostly arid to dryland fluvial systems and eustatic changes mostly influenced the Danish part of the Central Graben and reached the southernmost parts of the Egersund Basin by cyclic marine encroachments (Ziegler & Van Hoorn, 1989). Ephemeral systems usually terminate prior to reaching a standing body of water due to the arid climate evaporation, hence perennial lakes form when the fluvial discharge and water supply stream dominated over evaporation (McKie, 2014). McKie (2014) further states that the central North Sea Triassic was draining towards playa deposits and that base level was affected by the fluvial sediment supply and the regional subsidence resulting in little base-level fluctuations.

2.3 Arid Dryland Depositional Systems

Within arid drylands, common depositional systems are aeolian, alluvial-fluvial fans, fluvial systems, lacustrine environment and marginal marine systems (Jarsve et al., 2014; Mckie & Williams, 2009). Alluvial-fluvial fans in an arid dryland setting are located in areas where sedimentation is enhanced and downstream flows expand, such as topographic escarpments, fluvial fans are commonly larger than alluvial fans and sediments migrate into a fluvial system (Collinson, 1996). Dryland fluvial systems are subdivided into ephemeral and perennial types. Figure 3-6 and 3-7 from McKie (2014) shows the ephemeral fluvial system as dry rivers where flooding is depending on weather and climate whereas the perennial fluvial system has a continuous water flow. Lakes also have a perennial profile within a dryland setting and may then act as base level and basin for the river streams. Dryland fluvial channels may also form around inland saline lakes and marginal marine systems as sabkhas and playas (Friedman & Sanders, 1978).

Two types of basins characterized by climate are used to define the drainage of terminal fluvial systems (Hartley, Weissmann, Nichols, & Warwick, 2010). Endorheic basins are continental basins; they have no link to open oceans, the drainage occurs internally within the basin and they are not affected by changes in global sea level (Nichols, 2012). In endorheic basins, fluvial systems terminate into playas, lakes and deserts (Hartley et al., 2010). An exorheic basin, on the other hand, has an external drainage imply that the continental basin is connected to an open ocean (Weissmann et al., 2010).

Banham and Mountney (2013) studied how fluvial systems evolve in salt wall basins based on case studies from regions as the Paradox Basin (USA), the Pre-Caspian Basin (Kazakhstan), the North Sea (J-block, UK sector) and La Popa Basin (Mexico). The study generated generic models for fluvial transport and subsidence in salt structured arid to dryland basins shown in figure 2-4. The figures illustrate the different delivery styles, axial and transverse delivery were proposed for fill of the Skagerrak Formation Judy sandstone member in the UKCS J-block area. Banham and Mountney (2014) work on the Triassic Moenkopi Formation in the Salt Anticline Region, southwest USA, discuss that deposition was dominated by sheet-like mediums that were either channel belt complexes or sheet-like elements of broad fluvial streams.

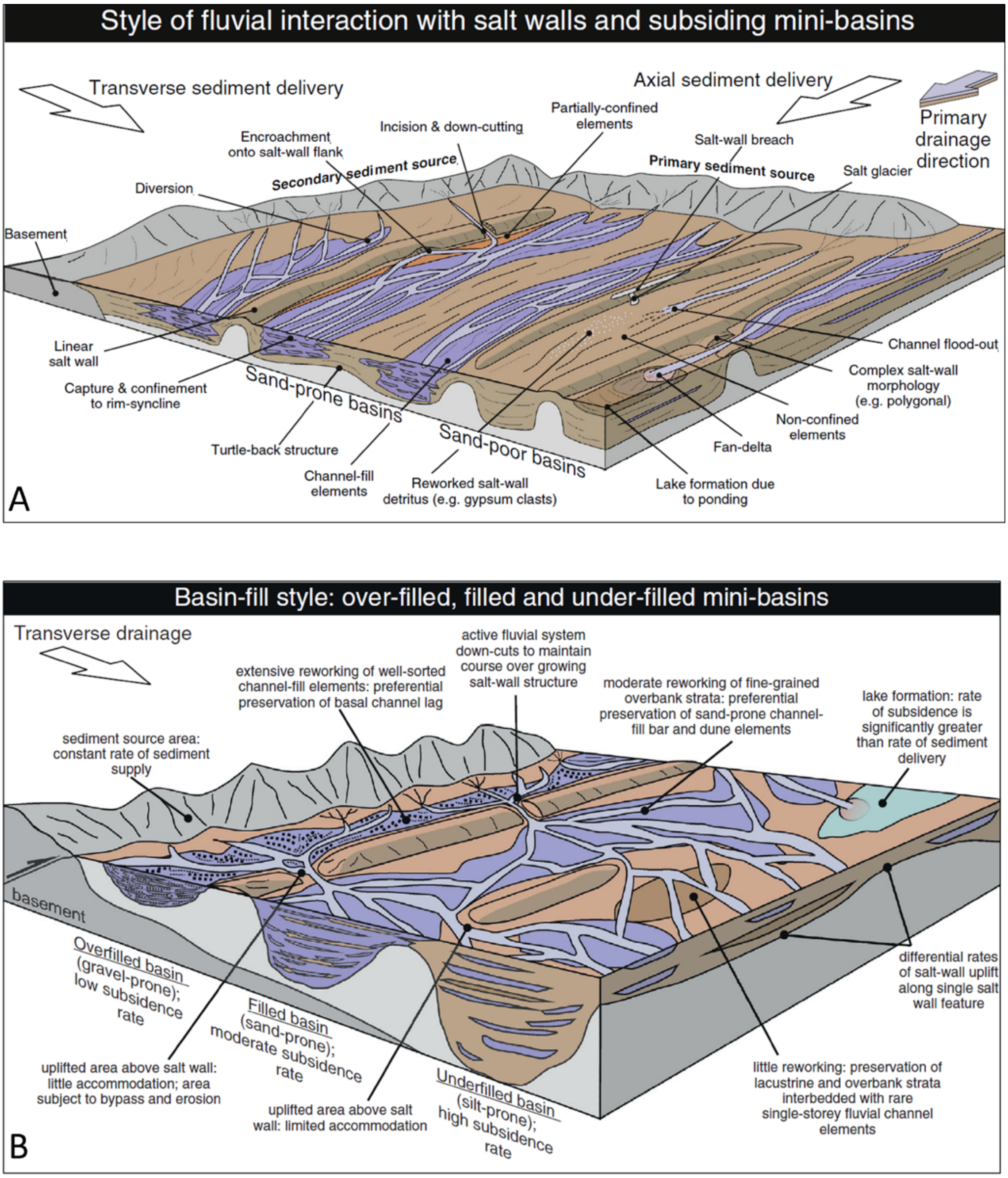


Figure 2-4 Generic models for the fluvial infill in salt walled minibasins. A) Axial delivery fills the basins parallel to the salt walls. B) Transverse delivery resulting in overfilled-filled and underfilled basins. (Banham & Mountney, 2013).

2.4 Controls on Sediment Delivery to Arid Alluvial-Fluvial Basins

Previously the semi-arid Skagerrak Formation was modelled as a sand prone braided fluvial system affected by halokinesis on the UK sector (McKie & Audretsch, 2005). However post drilling on the UK Heron cluster demonstrates the reservoir connectivity of the formation had been overestimated and the Skagerrak Formation was subdivided into sand and shale members by (Goldsmith et al., 2003; Goldsmith et al., 1995) (McKie & Audretsch, 2005).

2.5 Source-to-Sink

2.5.1 'Tectonically Active' Inter-Rift Basins

The Norwegian Danish Basin and the Egersund Basin were filled with Triassic clastic deposits as uplift and erosion of the Norwegian hinterlands e.g. the Stavanger Platform during the active extension of the Øygarden-Egersund Fault System (Goldsmith et al., 2003). Extensional tectonics generates uplift and erosion of footwall blocks, providing a proximal source for the fluvial systems (Goldsmith et al., 2003). The rivers in a dryland system might terminate prior to reaching the final basin as they evaporate and deposit onto the plains or may transport and deposit sediments to sink into the endorheic basins (Hartley et al., 2010). Due to Triassic rift episodes, an intra Triassic unconformity separates them to as two episodes of pod subsidence of the Smith bank and Skagerrak formations (McKie, 2014). McKie (2014) discuss that the Early to Middle Triassic sediments were a terminal fluvial system changing downstream to a dry playa setting (see chapter 3).

The Middle to Late Triassic has a wetter profile and fluctuated between playas and continuous fluvial systems depositing into perennial lakes (McKie, 2014). The vertical source to sink profile from the northern North Sea and the Norwegian Danish Basin have a proximal to distal fining profile (Goldsmith et al., 2003). Fluvial deposits in proximal setting comprise fine to coarse-grained cross-bedded sediments with local conglomerates transporting sediments to medial areas with finer grains and a more heterolithic setting finalizing in distal mud rich terminal fringes (McKie, 2017).

2.5.2 Salt-Basins

Salt basins create smaller pods or “minibasins” for sediments to accumulate. These pods may have different subsidence rates as sediments are deposited and regional tectonics is active (McKie & Audretsch, 2005). When the subsiding pods ground on pre-salt strata the basin is not subsiding further. Salt diapirs and walls may function as distributors and organizers of fluvial streams. This can be inferred from how the fluvial deposits are located along the salt basin. The size of the minibasins is controlled by the viscosity of the salt, overburden density and salt thickness (Banham & Mountney, 2013). Syn-rift deposits initially fill pods adjacent to salt between tilted basement fault blocks, whereas after salt structuring was more distinct depsition are more widespread and covers large basin areas (Goldsmith et al., 2003).

3 GEOLOGICAL SETTINGS

3.1 Introduction

The North Sea is a tectonically complex sedimentary basin that has undergone several tectonic extensional pulses since rifting began. The structural style of the North Sea is varying from the rift system dominating in the north to a salt influenced basin in the southern part (Zanella & Coward, 2003). For this study, the research is located within the salt influenced Central North Sea. The Palaeozoic era was marked by convergent plate settings, Mesozoic was characterized by rifting and halokinetic structuring and the Cenozoic era exerted compressional events on the Central North Sea Basin (Coward et al., 2003). The diverse tectonic pulses have subject great complexity to the North Sea and a challenging, complex geological setting.

3.2 Central North Sea

The Central North Sea is located in the southern part of the Norwegian North Sea (figure 3-1). The Central Graben is a symmetrical graben forming a branch of the Central North Sea triple junction (Mannie et al., 2014a). The Central Graben formed as a result of two main rift episodes during the Late Permian to Triassic and Middle Triassic to Middle Jurassic and post-rift thermal relaxation and subsidence followed the rift episodes in Late Cretaceous (Zanella & Coward, 2003). The Late Cretaceous and Cenozoic subsidence were disturbed by regional and local repetitively inversion in response to the Alpine Orogeny (Coward et al., 2003). In comparison with the other sections of the North Sea, the Central North Sea is a salt influenced prolific hydrocarbon sedimentary basin (Mannie et al., 2014a). The salt acts as a detachment surface (Zanella & Coward, 2003). The Norwegian Danish Basin (NDB) trends west-northwest –east-southeast and comprise thick Permian and Triassic aged sediments. The Jurassic rift phases separated the basin into sub-basin, e.g. the Egersund (Skjerven, Rijs, & Kalheim, 1983).

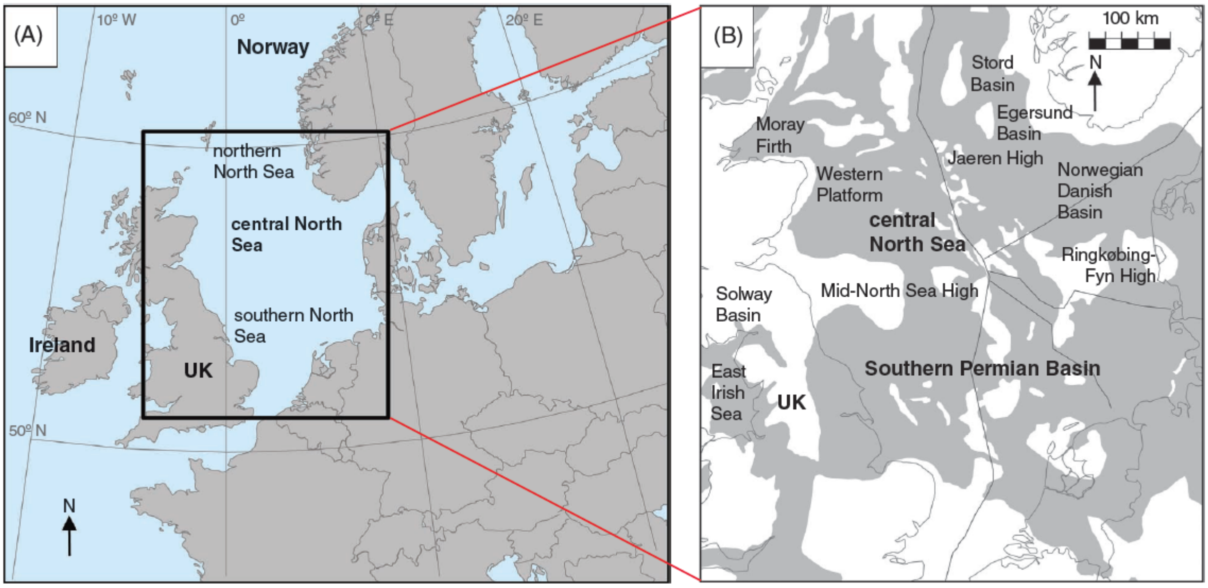


Figure 3-1 location of the Central North Sea and some of the belonging structural configurations (McKie, 2014).

3.3 Tectonic evolution of the Central North Sea

3.3.1 Permo-Triassic rifting

The initial extension forming the Central North Sea commenced in the Permian period as the Pangea Supercontinent broke up following orogenic collapsed followed by Early Permian post-rift (Jackson & Lewis, 2014; Ziegler & Van Hoorn, 1989). The rifting formed two large rift basins, the North and South Permian basins (Jarsve et al., 2014). Permo-Triassic rifting established grabens affected by the former Variscan thrusts (Zanella & Coward, 2003). Zechstein Group halokinesis occurred in the North Permian Basin in the Central North Sea as well as in the Southern Permian Basin (fig 3-2) (Karlo et al., 2014). Early Triassic rifting overprinted the North Permian Basin with a north-south trend generating the faults creating the Norwegian Danish Basin (Karlo et al., 2014).

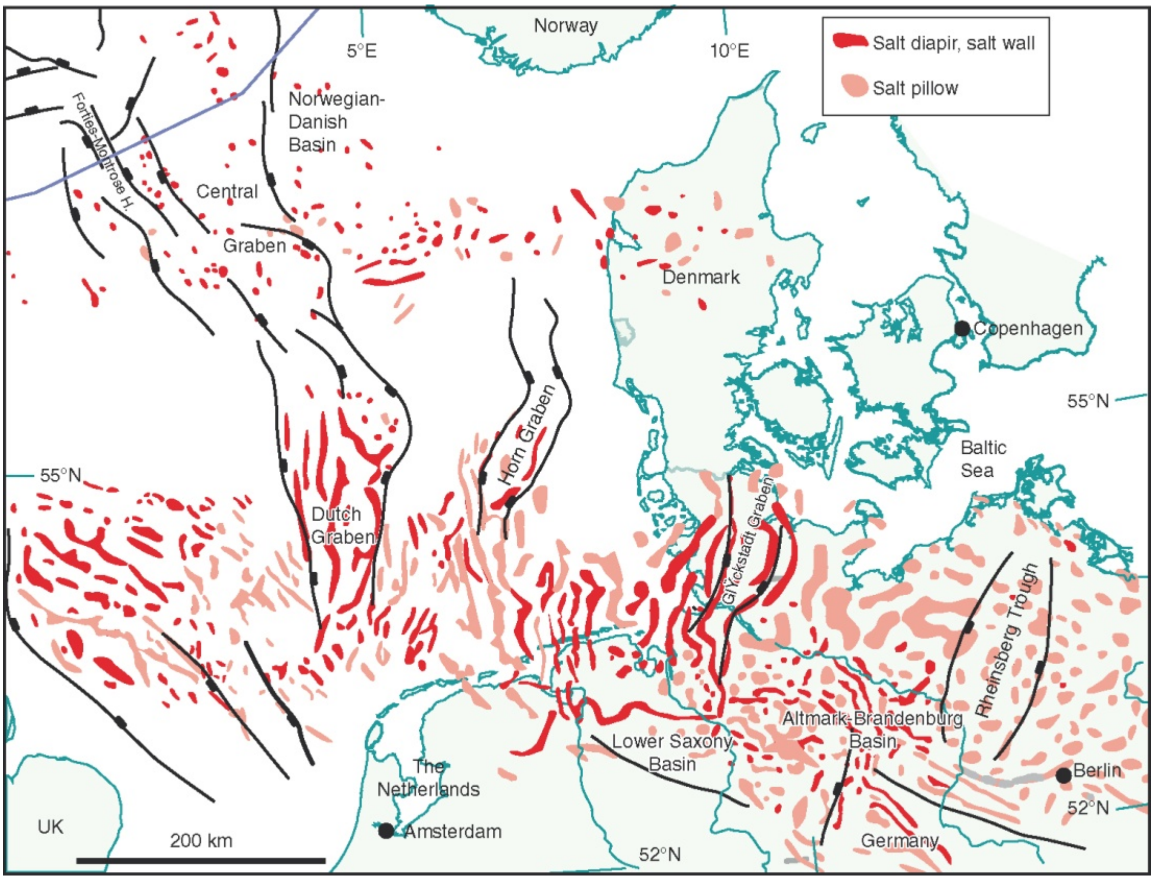


Figure 3-2 Distribution of the Zechstein Group structures in the Southern North Sea and northern Europe (Fossen, 2010; Scheck et al., 2003)

3.3.2 Triassic Rifting and Halokinesis

Upper Permian Zechstein deposits caused major halokinetic deformation in the Central North Sea, creating thickness variations due to diapirism, this generated small sub-basins trending northwards in a linear pattern (Goldsmith et al., 2003; Ziegler & Van Hoorn, 1989). The halokinetic stage originated in Early Triassic as a result of differential loading combined with extensional thin skinned rifting which terminated in Early Jurassic times (Banham & Mountney, 2013; Coward et al., 2003). Minibasins (pods) formed adjacent to the salt structures accumulating thick deposits of Triassic aged sediments (Mannie et al., 2014a). Two main rift phases; Early Triassic and Middle Triassic, following the break-up of Pangea (fig 3-3), defined the Triassic strata as syn halokinetic rifting, although there is little evidence of Triassic rift-related faulting in the Norwegian Danish Basin (Goldsmith et al., 2003; McKie, 2014).

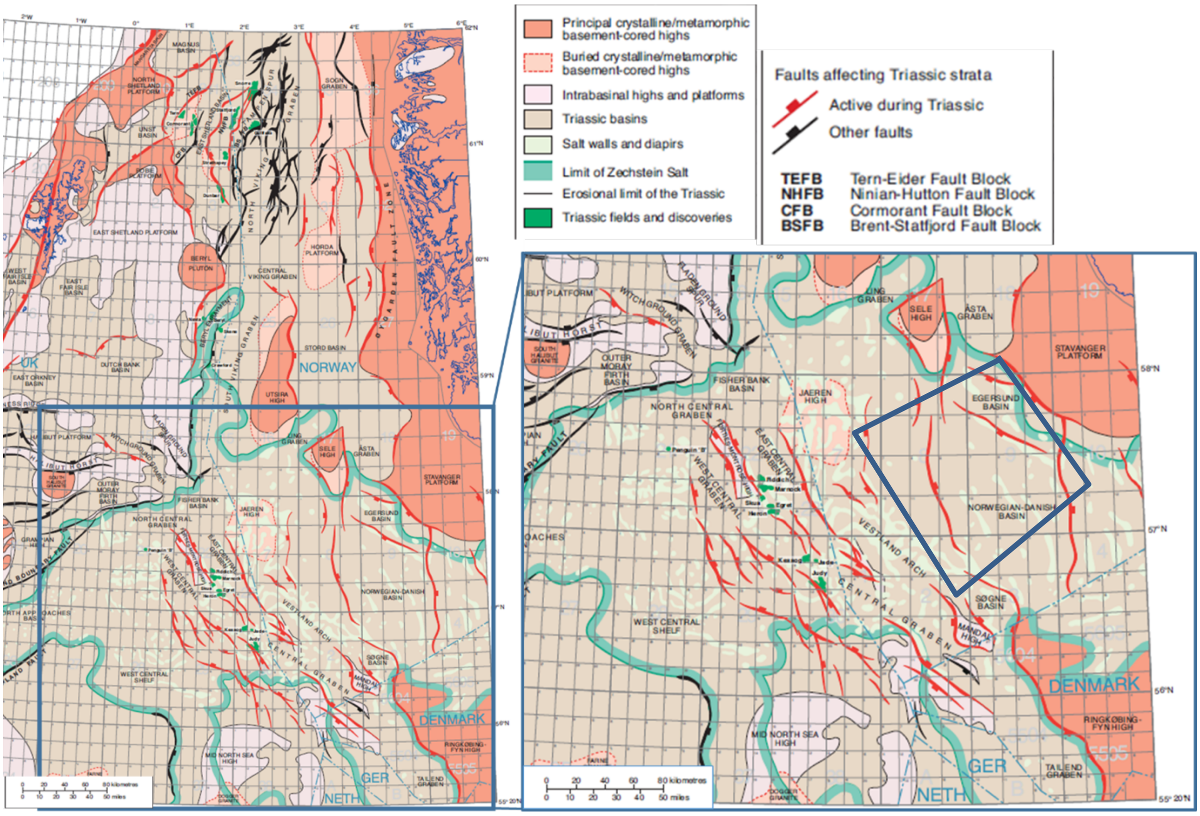


Figure 3-3 Tectonic elements from the Triassic period indicating an extensional setting during the Triassic period.(Goldsmith et al., 2003)

3.3.3 Middle Jurassic Thermal Doming

The Early Jurassic is marked as a tectonically quiet period with high rates of subsidence (Husmo et al., 2002). The Central North Sea was uplifted during the Early-Middle Jurassic thermal doming, which produced the Mid-Cimmerian unconformity due to an erosion of Triassic and Jurassic strata (Coward et al., 2003; Mannie et al., 2014a). The presence of volcanic rocks in the Central North sea implies that a mantle hotspot was present generating uplift of the Central North Sea area (Zanella & Coward, 2003).

3.3.4 Middle-Late Jurassic Rifting

The second rift phase commenced in the Late Jurassic and was most extensive in the period from mid- Callovian to Kimmeridgian lasting around 10 million years (Fraser et al., 2003). The rifting evolved the triple junction rift of the Central Graben, Viking Graben and the Moray Firth Basin generating the structural framework of the present North Sea Basin (Coward et al., 2003; Zanella & Coward, 2003). The extension in the central North Sea was trending in a NE-SW direction and the Jurassic extension reactivated Triassic faults with the same orientation and magnitude (Goldsmith et al., 2003; Zanella & Coward, 2003).

3.3.5 Early Cretaceous Post-Rift & Structural Rejuvenation

The Early Cretaceous stage of rifting continued from the active Jurassic rifting but shifted west to form the proto-North Atlantic rifting (Copestake et al., 2003). Whilst the locus of extension shifted, the intra-plate differential stress field overlapped with passive thermal subsidence in the central North Sea area and transgression formed the Base Cretaceous Unconformity (BCU) (Copestake et al., 2003; Coward et al., 2003). In the Early Cretaceous, salt dissolution occurred on the basement highs and created large thickness variations in the Lower Cretaceous deposits, whereas during the mid-Cretaceous period salt dissolution ceased and remobilizations of salt mostly terminated in sub-basins (Stewart & Clark, 1999).

3.3.6 Late Cretaceous Post-Rift & Central North Sea Inversion

The Late Cretaceous period was dominated by subsidence disturbed by regional inversion that occurred as compressional events from the Alpine Orogeny, the North Atlantic rifting and chalk deposition over the CNS (Jackson & Lewis, 2016; Surlyk, Dons, Clausen, & Higham, 2003). The compressional event induced rejuvenation of the Central North Sea salt structures. The effect of the compressional event diminishes northwards in the Central North Sea and is very weak in the northern North Sea (Stewart & Clark, 1999; Zanella & Coward, 2003).

3.3.7 Early Paleogene Intracratonic Basin with Inversion

Subsidence was the main tectonic event during the Early Paleogene times (Ahmadi et al., 2003). The North Sea also underwent inversion during Early Paleogene as the North Atlantic started to spread and its propagation changed spreading direction (Coward et al., 2003). In addition to the Atlantic spreading the East Shetland Platform was uplifted in the Paleocene-Eocene times (Jarsve et al., 2015).

3.3.8 Late Neogene Subsidence

Neogene was dominated by the closing of the Thetys Ocean and the continued seafloor spreading of the Atlantic alongside with steady subsidence (Fyfe et al., 2003). Accelerated uplift of basin flanks occurred in middle to late Miocene which was followed by basin subsidence in Pliocene time, which allowed for two till three kilometer thick columns of sediments (Fyfe et al., 2003)

3.4 Structural Elements in the Study Area

The study area is a symmetrical intracratonic graben comprising different elements such as platforms, half grabens and basins (figure 3-4). The study area is situated over the Northern

Permian Basin and comprises the Norwegian Danish Basin, the Sørvestlandet High, the eastern flank of the Central Graben and the western flank of the Egersund Basin (figure 3-4, Jarsve et al., 2014). Including the elements, two major fault zones are also covered within the area, the Coffee Soil Fault and the Hummer Fault Zone.

3.4.1 Central Graben

The Central Graben is a branch of the North Sea triple junction system connected to the Moray Firth Basin and the Viking Graben (figure 3-4). The main development occurred in the Late Jurassic but Triassic/ Middle Jurassic extension may have opened the proto Central Graben (Zanella & Coward, 2003). The graben is trending northwest-southeast and the graben was actively faulting and subsiding in Mesozoic comprising closely spaced, rotated normal faults (Skjerven et al., 1983).

3.4.2 Sørvestlandet High

The Sørvestlandet High is located east of the Central Graben and west of the Norwegian Danish Basin as seen on figure 3-4. It is a structural high extending 25 kilometers in a northwest to southeast trend with internal normal faults with a north-south trend (Ge, Gawthorpe, Rotevatn, & Thomas, 2017).

3.4.3 Norwegian Danish Basin

The main structural element within the study area is the Norwegian Danish Basin, comprising the Åsta Graben, which has a west-northwest to east- southeast orientation (Skjerven et al., 1983). The Basin is situated in the North Permian Basin and was formed by subsidence after the early Permian extensional tectonics (Jackson & Lewis, 2016).

3.4.4 Egersund Basin

The basin has a northwest-southeast trend, is located in the eastern part of the central North Sea and is a Jurassic sub-basin of the Norwegian Danish Basin (Tvedt, Rotevatn, Jackson, Fossen, & Gawthorpe, 2013).

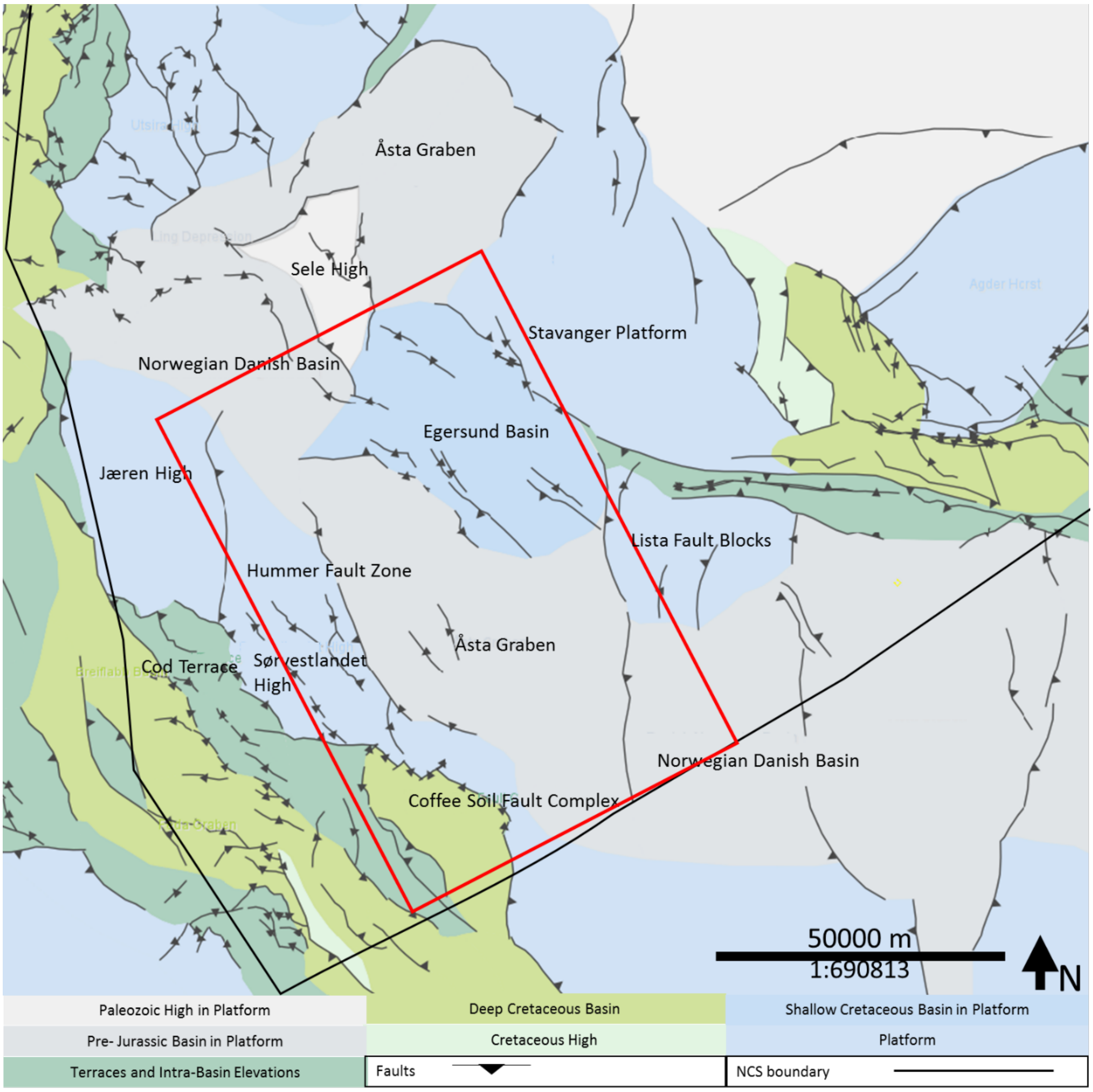


Figure 3-4 Structural elements located within the study area, color legend defined from NPD (2019e)

3.5 Stratigraphy of the Norwegian Central North Sea

The sedimentary infill history (fig 3-5) in the North Sea goes back to Devonian times and lay on Precambrian and Palaeozoic basement from the Caledonian Orogeny (Zanella, Coward, & McGrandle, 2003). In the central North Sea, the Triassic deposits are thickening towards the east from the Central Graben axis (Zanella & Coward, 2003). The stratigraphic column of Triassic sediments is thicker in the Viking Graben (3000 meters) than in the Central Graben (2000 meters), where the Central Graben holds a maximum thickness of 2000 meters. (Ziegler & Van Hoorn, 1989). The Central North Sea- Norwegian Danish Basin stratigraphy is summarized in figure 3-5. The figure illustrates the arid nature of the Triassic in comparison to younger strata.

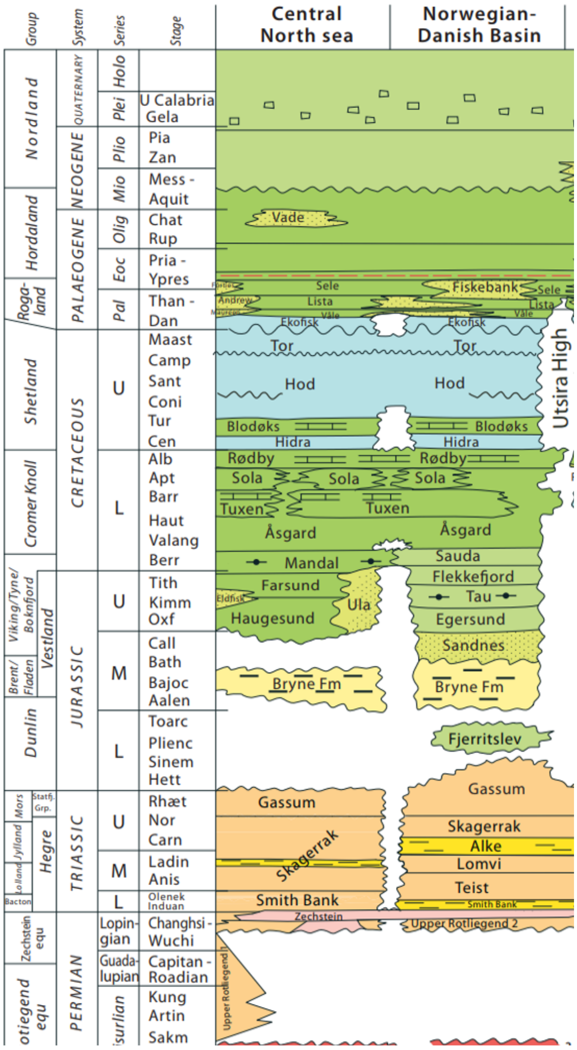


Figure 3-5 Stratigraphic chart of the Central North Sea and the Norwegian Danish Basin from the Permian period to Holocene. Modified from (NPD (2011))

3.6 (Late Permian to) Triassic Stratigraphy and Paleogeography

During Permian and Triassic, the Central North Sea was situated near the equator. It was part of the supercontinent Pangea and had an equatorial arid environment (Hounslow & Ruffell, 2006). The Permian Zechstein Supergroup was an epicontinental sea situated in the Northern and Southern Permian basins as global sea level rose (Glennie et al., 2003). The Zechstein Sea was surrounded by an arid desert climate and the evapotranspiration was to the magnitude that it outpaced normal marine circulation generating hypersaline bottom waters depositing salt (Banham & Mountney, 2013; Smith & Taylor). At the start of the Triassic period the Smith Bank Formation was deposited in a distal arid terminal fluvio-lacustrine environment (fig 3-6) (Banham & Mountney, 2013; Goldsmith et al., 2003). The formation was mostly sourced from the UK by the erosion of Caledonian metasediments and is analogous to the existing Lake Eyre basin (McKie, 2014).

Figure 3-6 Conceptualized ephemeral fluvial system corresponding to the Smith Bank Formation in the Central North Sea. The upper figure shows the proximal style of an ephemeral system. The Lower is illustrating the distal regions with playa deposits and terminal splays. (McKie, 2014)

Middle to Upper Triassic strata is composed of the Skagerrak formation. The formation consists of sand-rich deposits that formed in a terminal dryland fluvial system under semi-arid conditions system in the Central North Sea (fig 3-7) (McKie, 2014). The Lower part of the Skagerrak Formation was sourced from the Shetland Platform, whereas the Upper part was dually-sourced from Fennoscandia and Scotland (Banham & Mountney, 2013; Mange-Rajetzkey, 1995). As the continents drifted northwards the environment of the Central North Sea turned semi-humid resulting in an Early Jurassic marine transgression (Mannie, Jackson, & Hampson, 2014b). The Skagerrak Formation is subdivided into the Judy, Joanne and Josephine sandstone members and the Julius, Jonathan and Joshua mudstone members. The Judy and Joanne members are the primary hydrocarbon reservoirs in the adjacent Central Graben (Banham & Mountney, 2013).

The stratigraphy of the Skagerrak Formation sandstone members comprises massive fluvial sandstone bodies with fine to medium-grained sediments in the Judy member, the Joanne member with fine-grained deposits and medium to coarse-grained channel fill to fine-grained clean sands of the upper Josephine member (Goldsmith et al., 1995). The mudstone members are the Julius, Jonathan and Joshua members (Goldsmith et al., 2003). Due to the Middle Jurassic doming, the uppermost Josephine and Joshua members of the Skagerrak Formation are commonly eroded away in parts of the Central North Sea and only preserved in very deep basins (Kape et al., 2010).

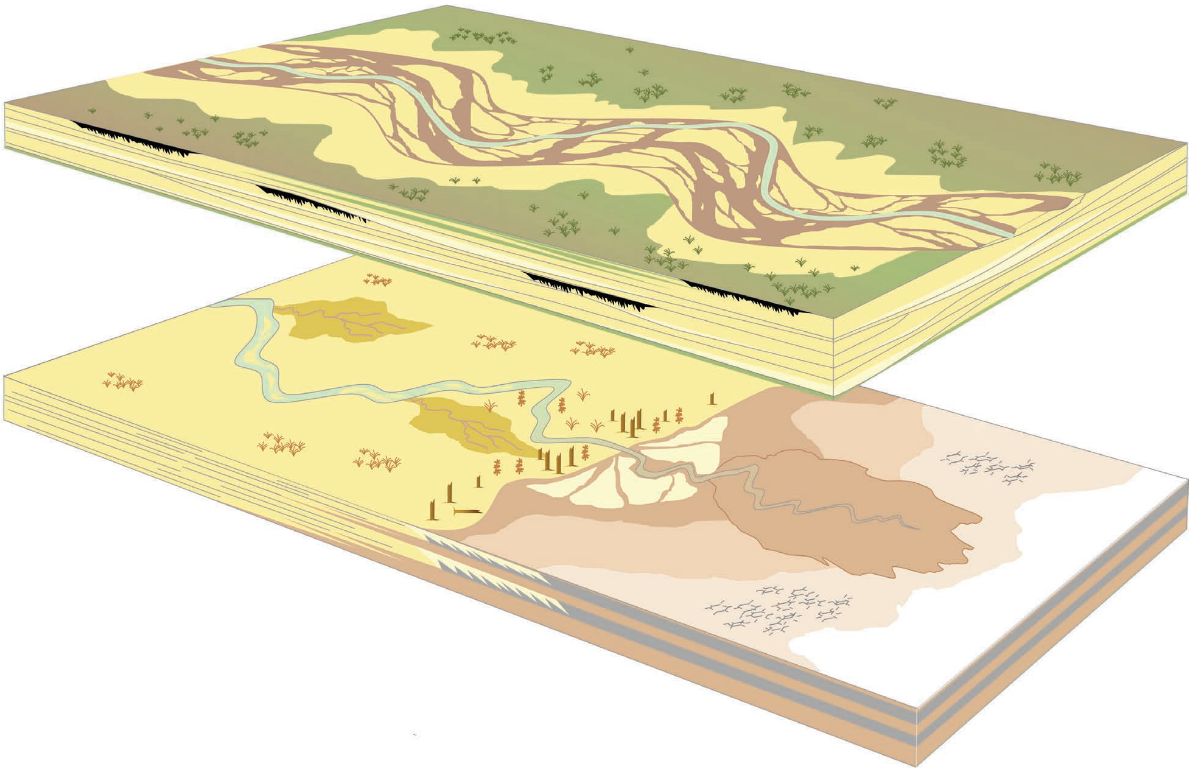


Figure 3-7 Conceptualized figure of the Perennial fluvial style from the Upper Triassic Central North Sea. The upper figure shows the sand prone proximal style with channel bar deposits. The lower figure illustrates the distal setting with interbedded floodplains and playas. (McKie, 2014).

4 DATABASE & METHODOLOGY

4.1 Introduction

The research done in the study area carried out an integrated seismic study of the Triassic succession in the Norwegian Danish Basin. Seismic data were the main dataset used in the study whereas well- and core data has been utilized to support seismic interpretations. The study has been carried out using Schlumberger's E&P software Petrel and consist of a number of 2D surveys.

4.2 Database

4.2.1 Approach

The study involves an investigation of a regional seismic interpretation within the study area, the Norwegian Danish Basin, using 2D seismic data. The interpretation comprised mapping of four key horizons; top Triassic, top Lower Triassic, top Zechstein Group and top Rotliegend Group. The Triassic strata were separated into two units. To constrain lithology of the seismic Triassic units, well logs and core data were supplied to the dataset.

4.2.2 Seismic Dataset

The seismic dataset was provided by Aker BP and comprised a vast amount of regional 2D seismic reflection lines from different surveys (fig 4.1). The surveys available were NSR03, NSR03R06, NSR04, NSR05, NSR06, GNSR91, CGME96, SHD97, SHDE98 and SHDEI98 (see table 4-1). The dataset covers an area of 19495.303 km^2. Of the included 2D surveys, the NSR surveys were the reference lines as they were produced more recently and thus comprise enhanced seismic quality. The seismic surveys are of good quality but the succession of interest have poorer resultion in comparison to the overlying strata.

Table 4-1 Table of the 2D seismic surveys used in the study.

Survey	NSR03	NSR03R06	NSR04	NSR05	NSR06	SHD97	SHDE98	SHDEI98	CGME96	GNSR91
Type	2D									
Polarity	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Navigation lines	10	9	92	82	129	59	35	39	34	68
Location CRS	ED50/ UTM31									
Quality	Good	Good	Good	Good	Good	moderate	Moderate	Moderate	Moderate	Moderate
Resolution	Lower Triassic, T1: 62 meters					Upper Triassic, T2: 68 meters				

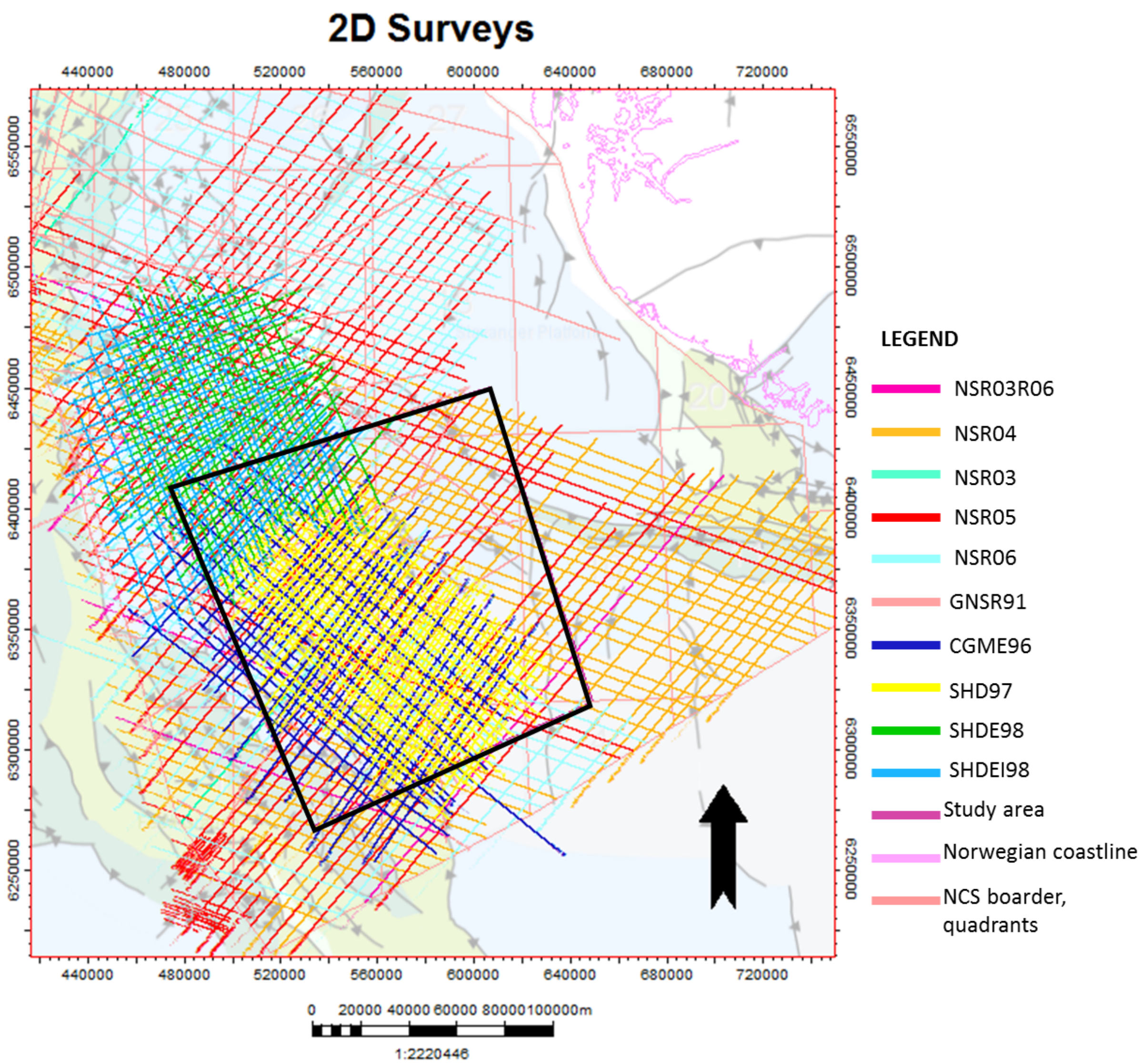


Figure 4-1 Outline of the 2D seismic survey datasets included in the work.

4.2.3 Seismic Resolution

The target succession is located at depths between 2500 ms to 6000 milliseconds. This has a significant effect on the seismic quality as the depth and compaction distorts the imaging of the strata. The Triassic succession consists of mostly low amplitude, discontinuous reflectors generating low quality seismic. The dominant frequencies for the succession were measured between 13-23 Hz. For the Lower Triassic Unit T1 the dominant frequency was determined to 20 Hz and for the Upper Triassic Unit T2 the dominant frequency was 15 Hz. The interval velocities of the Units were respectively: 4968.23 m/s in the Lower Triassic Unit T1 and 4113.8 m/s for Upper Triassic Unit T2. For the resolution, see table 4-1 and equations 4-3 and 4-4.

$$Unit\ T1\ \Delta Z = \frac{4968{,}23\ m/s\ /\ 20\ Hz}{4} = 62\ meters \qquad \text{Eq. 4-3}$$

$$Unit\ T2\ \Delta Z = \frac{4113{,}8\ m/s\ /\ 15\ Hz}{4} = 68\ meters \qquad \text{Eq. 4-4}$$

The resolution and the quality of the seismic data affects the interpretation competence. Table 4-2 summarizes the interpreted horizons and their respective age, reflector type, amplitude response and interpretation confidence.

Table 4-2Showing the interpreted unit tops for the study,

Surface	Top Rotliegend	Top Zechstein	Triassic Unit T1	Triassic Unit T2
Age of formation	Permian	Late Permian	Early Triassic	Late Triassic
Reflector	Peak	Trough	Trough	peak
Amplitude	Strong	Strong & weak	Strong	Weak & Strong
Confidence	Strong	moderate	moderate- low	Moderate to low

4.2.4 Well Dataset

An abundance of exploration wells were included in the dataset whereas not all penetrate the Triassic succession. The wells are distributed in quadrants 1, 2, 4, 7-11, 16-18 (figure 4-2, table 4-3). Triassic formations comprised in the well dataset are the Smith Bank Formation and Skagerrak Formation formation. GR log motif will be used to identify the Triassic units defined from the seismic analysis. For the study, only wells drilled deep enough to penetrate Triassic strata were used, see table 4-3 for an overview of the different logs.

Table 4-3 The wells included for the main research and used for seismic-well tie.

Wells	Line Tied	Bulk Shift (ms)	Wavelet	GR	DT	RHO	POR	CALI	Check shots	Oldest formation
1/6-5	NSR05-32318	15	Statistical extraction	Yes	Yes	No	Yes	Yes	Yes	Zechstein
2/1-10	NSR04-32322	-15	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak
2/3-3	NSR05-42311	18	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Zechstein
7/3-1	NSR06-42337	-10	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Rotliegend
7/12-6	NSR05-32326	8	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak
7/12-10	NSR06-41103	2	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak
8/3-2	NSR04-31122	20	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak
8/10-1	NSR06-41103	2	Statistical extraction	Yes	Yes	No	No	Yes	Yes	Zechstein
8/10-2	NSR04-32322	10	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Zechstein
9/2-1	NSR04-42321	5	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak
9/4-5	NSR04-42321	20	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Rotliegend
9/11-1	NSR05-41107	20	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak

10/5-1	NSR05-22308	10	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Zechstein
16/2-11	NSR04-11136	0	Statistical extraction	No	Yes	Yes	Yes	Yes	Yes	Skagerrak
16/4-1	NSR06-32354	-15	Statistical extraction	No	Yes	Yes	Yes	Yes	Yes	Rotliegend
16/10-2	NSR04-11120	15	Statistical extraction	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak
17/10-1	NSR05-12336	10	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Smith Bank
18/10-1	NSR05-411271	10	Ricker 25 Hz	Yes	Yes	Yes	Yes	Yes	Yes	Skagerrak

Well logs will contribute with implications of net to gross of the Triassic packages as well as identifying the stratal differences in the Triassic units. A map over the well log distribution is seen in figure 4-2 A) well database available for the study, B) wells used to conduct well ties for the area.

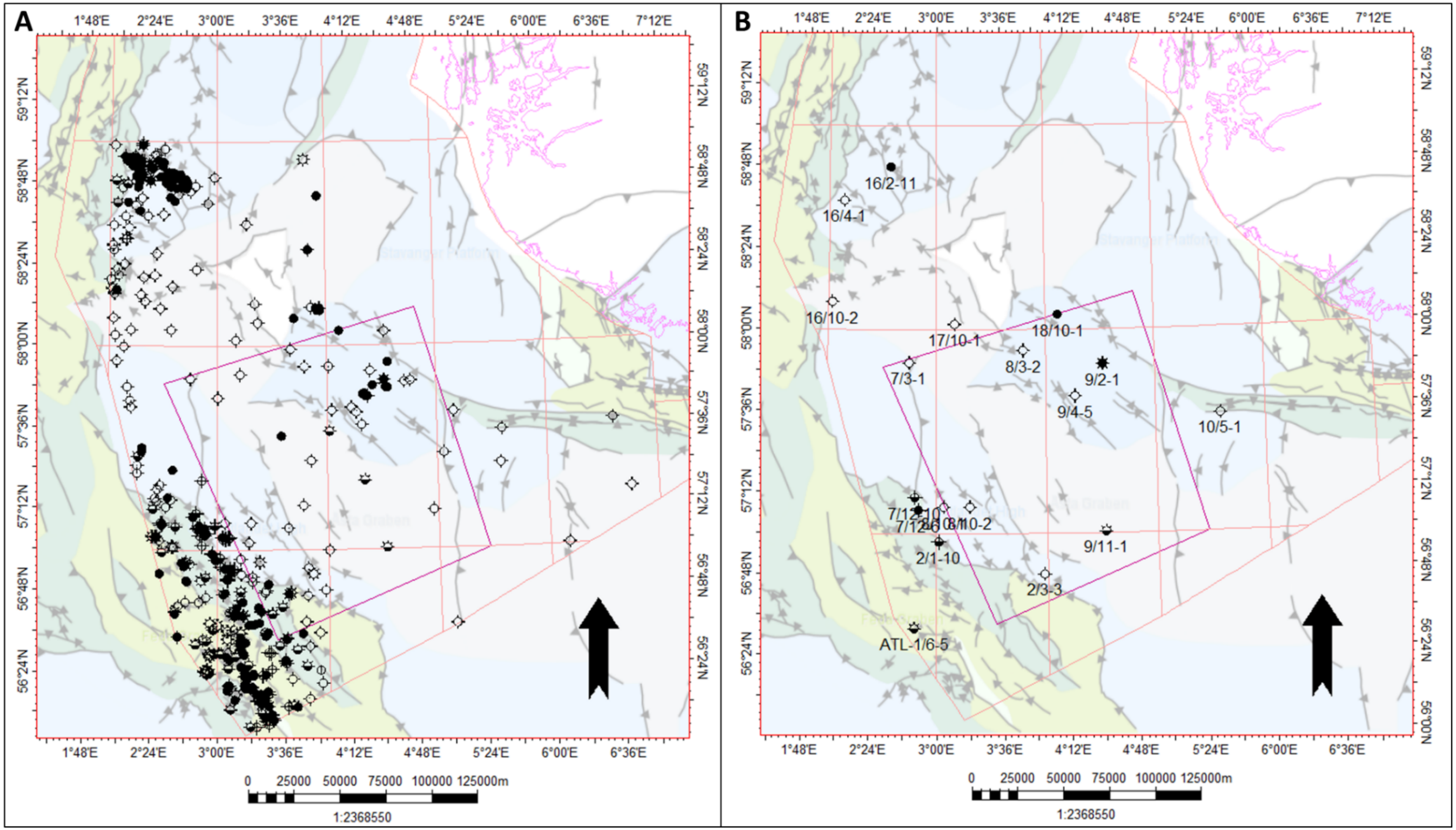


Figure 4-2 A) Well database available for the study. B) Wells used to execute well ties to tie the Triassic and Permian horizons.

4.2.5 Core Data

Different cored intervals were available for this study through Aker BP (table 4-4). The core data investigated for this study were situated around the Ula and Oda fields. Core data from outside the study area were also inspected to apply for the study area. The distribution of the cored intervals is show in figure 4-3.

Table 4-4 Table summarizing the core information available for the thesis work. The emphasis has been put on well 7/12-6 with complete availability of the Skagerrak Formation.

CORE NAME	CORE SAMPLE	METERS
7/12-A-7	Core 3-6	57 m
7/12-A-15	Core 5	12 m
7/12-2	Core 11	19 m
7/12-6	Core 5-9	133 m
7/12-10	Core 2	27 m
7/12-11	Core 1	10 m
8/10-4-S	Core 3	25 m
8/10-5-S	Core 2	20 m

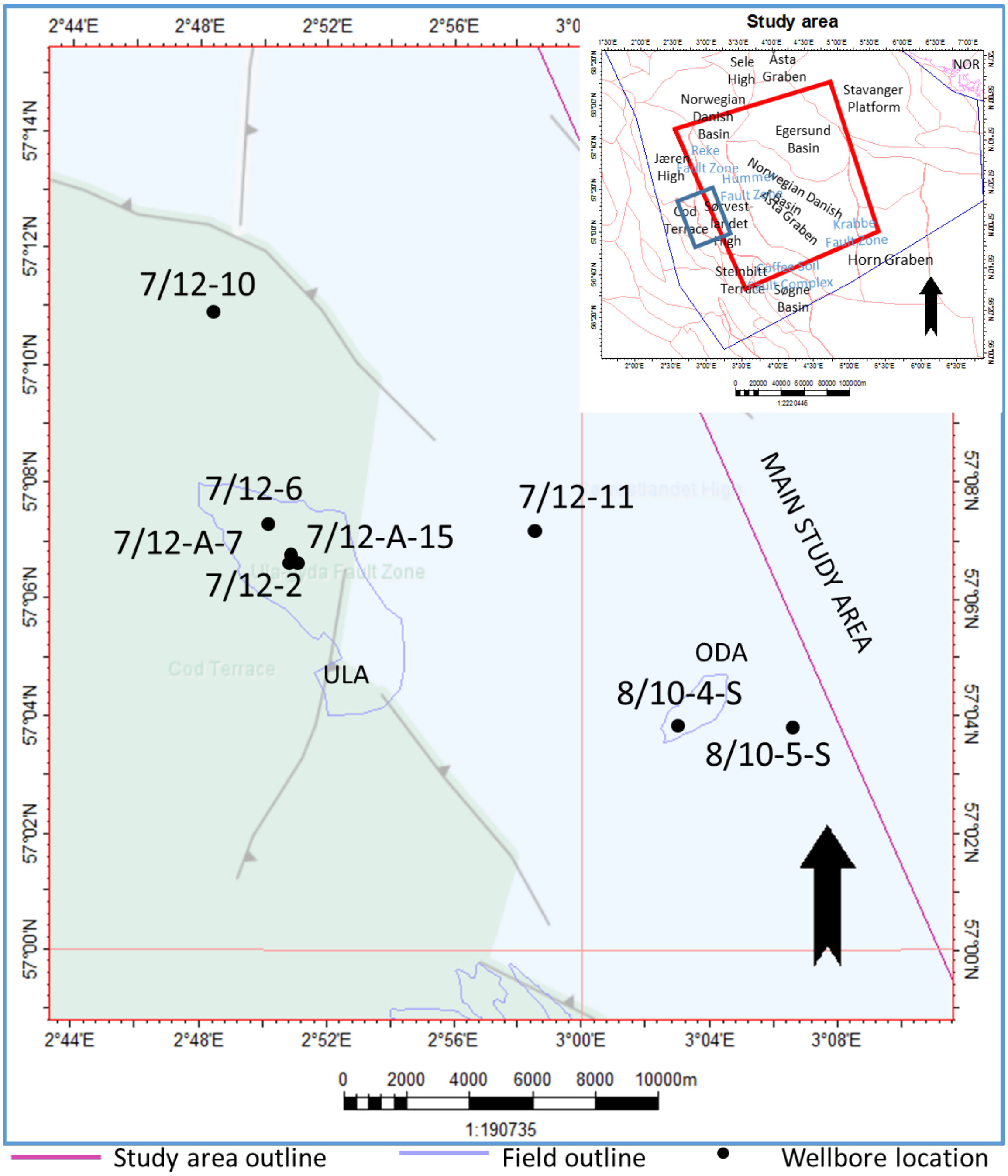


Figure 4-3 Distribution of cored intervals available for the thesis work

4.3 Methodology

4.3.1 Approach

The first step of the investigation was a regional seismic interpretation within the study area of the Norwegian Danish Basin using 2D seismic data. The interpretation comprised mapping of four key horizons; top Triassic, top Lower Triassic, top Zechstein Group and top Rotliegend Group. The key horizons were tied to the well data using well logs and amplitude changes. Lithological constraint to the seismic packages was done by interpretation of well logs and core data.

4.3.2 Seismic Polarity Determination

Seismic polarity was determined by extracting the wavelet of the seismic surveys. By using this method in combination by determining the seabed reflector the polarity of the 2D surveys are defined to have American positive polarity (figure 4-4 A), hard kicks are presented by a peak reflector (fig 4-4 B).

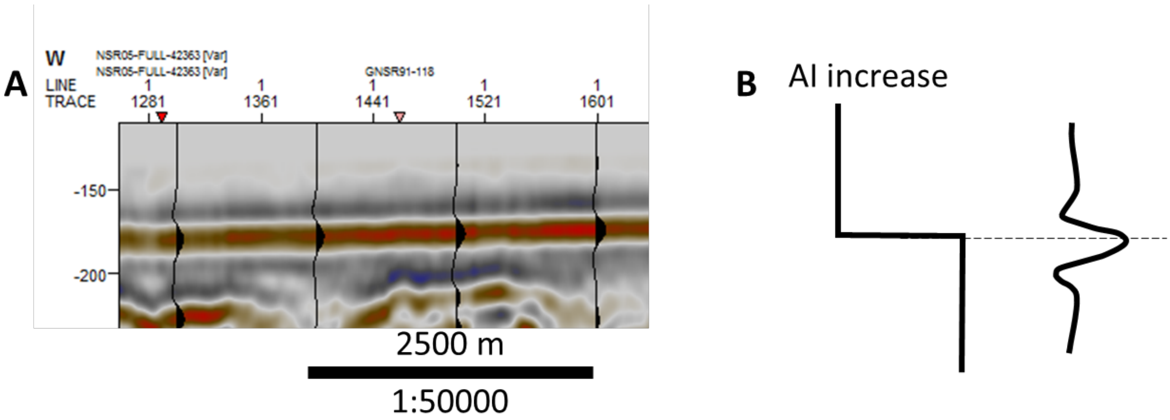


Figure 4-4 A) Polarity of seabed reflector in the seismic data. B) A simplified figure of increase in polarity.

4.3.3 Seismic Interpretation Workflow

4.3.3.1 Structural Interpretation

The structural interpretation included interpretations of fault complexes and salt structures in the seismic dataset.

4.3.3.1.1 Fault Interpretation

The interpretation of faults was done sub-parallel-to parallel onto the strike of the faults. Faults were interpreted as fault complexes. The fault complexes were generated based on displacement and alignment to the neighboring seismic lines. Sub salt faults were divided into fault complex families based on the strike and the dip direction of the complexes.

4.3.3.1.2 Volume Interpretation

The variance volume attribute was applied to the seismic data to enhance the location of salt diapirs to increase the interpretation confidence of the Zechstein Group (fig 4-5 B). The variance attribute uses an edge method to generate discontinuity differences between adjacent seismic responses. This was used to generate contrast in cross-sections between the transparent to chaotic Triassic and the Zechstein Group salt diapirs. The variance interpretation was compared to the ordinary seismic data to modify and provide a more exact interpretation.

4.3.3.2 Horizon Interpretation

The Rotliegend, Top Lower Triassic Unit T1 and Top Upper Triassic Unit T2 were interpreted using both guided auto track and manually based on the reflector continuity. The Zechstein horizon was interpreted using the Multi Z tool in Petrel. The four horizons interpreted are seen in figure 4-5 A.

4.3.3.2.1 Top Rotliegend Group

A strong amplitude peak reflector represented the top Rotliegend Group reflector. The amplitude was generally strong over the study area with few exceptions of very low amplitude contrast. The reflector was defined as a continuous reflector in most areas of the dataset. The interpretation confidence is strong as the high amplitude provides an easy correlation throughout the study area.

4.3.3.2.2 Top Zechstein Group

A trough reflector represented the Top Zechstein Group horizon. The amplitude of the horizon varies through the seismic data, from strong to weak. Were the reflector concordantly overlies the underlying reflector the amplitudes are strong. The continuity of the reflector is poor as the salt is distributed into diapirs. Salt has a plastic behaviour, pure Halite has density of 2,61 g/cm3 and higher if mixed with other evaporitic minerals and salt movement is initiated by either differential loading, tectonic pulses and a combination of both (Fossen, 2010). Due to the properties of salt, the Top Zechstein horizon was interpreted using Petrel's multi-Z tool to map it as a complete geometrical body. The interpretation confidence for the salt is strong to moderate.

4.3.3.3 Top Lower Triassic Unit T1 (T1)

The Lower Triassic Unit T1 top horizon was interpreted as a trough reflector. The top reflector defined as unit T1 was based on seismic facies amplitude response. It was mapped as strong negative amplitude reflector. The strong amplitude reflector was mapped in adjacent sedimentary pods and otherwise extrapolated to pods with weaker amplitudes using a grid of 2D lines. Amplitude variations were strong for the reflector mapped to represent the top horizon. The reflector has limited continuity, which provides a low to moderate confidence were the top reflector was close to transparent.

4.3.3.3.1 Top Upper Triassic Unit T2 (T2)

The top reflector of Unit T2 was interpreted and defined as a peak reflector event with amplitude variations. The amplitudes were mostly moderate but fluctuated from having a strong to weak amplitude contrast. The continuity of the reflector is poor and hence the interpretation confidence is defined as moderate to low. The top reflector of the unit was defined from conducting seismic well ties at different locations in the study area.

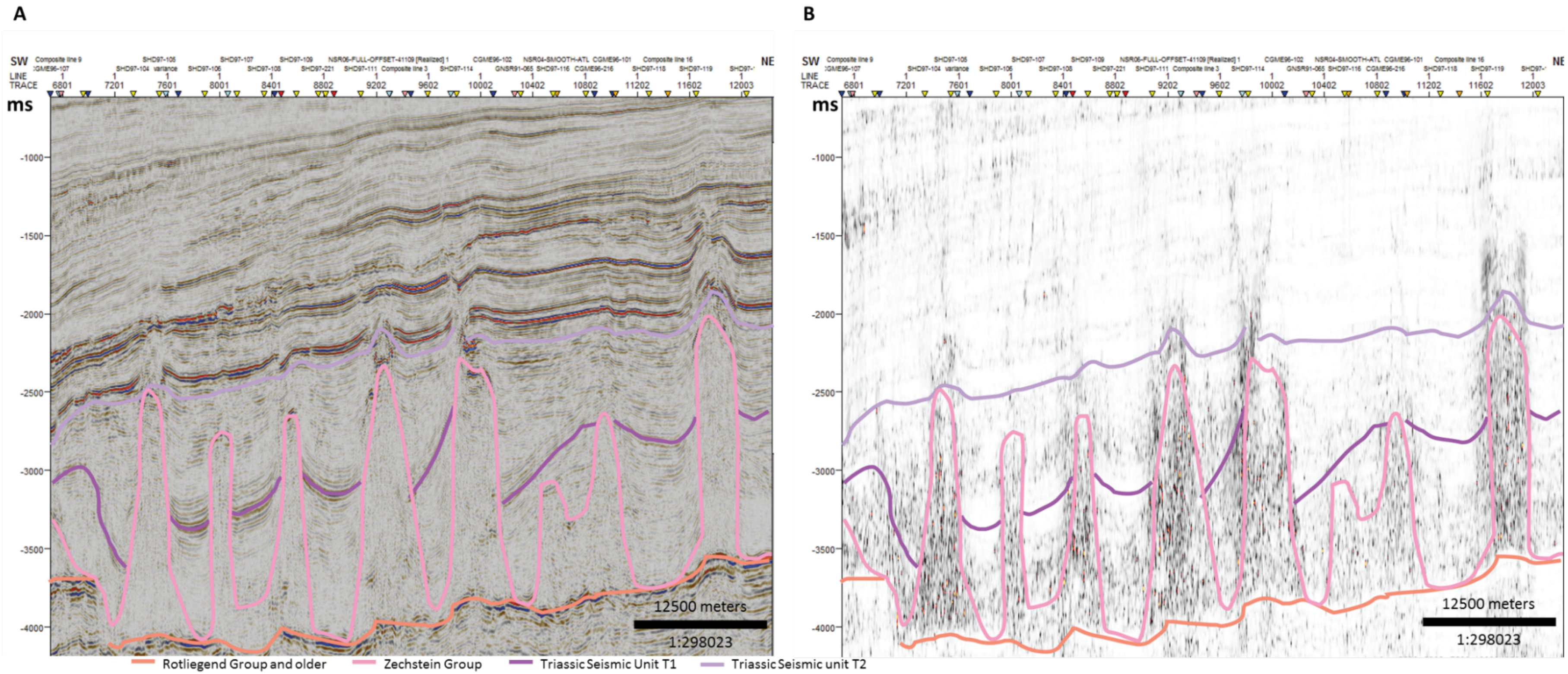


Figure 4-5 A) Stratigraphic horizon interpretation of the four key horizons. B) Variance volume attributed applied to interpret the salt geometry based on discontinuity contras

4.3.3.4 Map Generation

Surface maps were generated of the interpreted horizons to represent the structural depth differences in time and variations throughout the surface. Surface calculations were done on the Triassic unit structure maps to merge the salt interpretation with the horizon interpretations. The method used was to account for areas where the Zechstein surface had a higher elevation than the Triassic surfaces. Isochore maps were generated for the Zechstein salt, seismic Unit T1 and seismic Unit T2 to mark thickness changes and depocenters in the salt structuring and the Triassic deposits.

4.3.3.5 Amplitude Interpretation

Differences in seismic amplitudes were interpreted to separate the salt diapirs from the Triassic succession. In most areas, the amplitude response of the clastic deposits has stronger amplitudes with respect to the internal amplitude response of the salt. Top salt reflectors of some salt diapirs comprise strong amplitudes and were used to determine the rise of salt diapirs.

Amplitude contrasts were also used to define the Triassic units. A strong amplitude seismic marker defines the boundary between Lower Triassic Unit T1 and Upper Triassic Unit T2. The marker was used to defined the changes from the units.

4.3.3.6 Seismic Unit Determinations

The Triassic succession was separated into two seismic units based on amplitude differences. A strong amplitude reflector within the sub-basins was used to separate the units. The seismic maker event was chosen as the boundary between Lower Triassic Unit T1 and Upper Triassic Unit T2 as it is a semi-regional marker apparently present over large areas of the dataset. The amplitude response within in the seismic units was used to determine the packages as the lower package Unit T1 has generally lower amplitude contrast than the upper packages Unit T2.

The Triassic strata were divided into two seismic units, respectively Lower Triassic unit T1 and middle to Upper Triassic unit T2. Age determinations of the two units were discussed in chapter 5 and 6. Unit T1 is bounded by top Zechstein as its base and a strong amplitude seismic marker as its upper boundary. The upper Triassic unit T2, on the other hand, were bounded at its base by the strong amplitude seismic marker and the top Skagerrak Formation as the unit top.

4.3.3.7 Restoration

A cross-section line transecting from NE to SW were reconstructed using the software MOVE^{TM}. The restoration was done with support from Hugh Anderson from Aker BP. The restoration was done for the Triassic packages by removing and unfolding stratigraphical units. All deposits above the Triassic succession were accounted as one package. The strata were Post Triassic, Upper Triassic Unit T2 and Lower Triassic Unit T2. The units were removed and unfolded to de-compact the units. The final step was to restore the Rotliegend underlying strata.

4.3.4 Well Log Data Methodology

The well data were used to constrain the seismic to geological ages from the well logs through a seismic well tie. The well logs were then used to define lithology, sand content and net to gross of the seismic units interpreted in seismic data.

4.3.4.1 Seismic Well Tie

Seismic to well tie was conducted by generating synthetic seismograms (Figure 4-6). It was done using wells distributed in different locations within the study area. In table 4-3 an overview of bulk shift and well data are found. A maximum of 20 ms of bulk shift was applied to the seismograms and ties requiring a higher bulk shift were not considered in this thesis. The seismic to well tie were used to tie the Skagerrak Formation, as the top Triassic, to the seismic data. For the Lower Triassic Unit T1 top reflector a well tie was not conducted as it was based on seismic amplitude contrast. The Upper Unit T1 is rarely penetrated by boreholes as most well are terminated in the upper parts of the Triassic succession

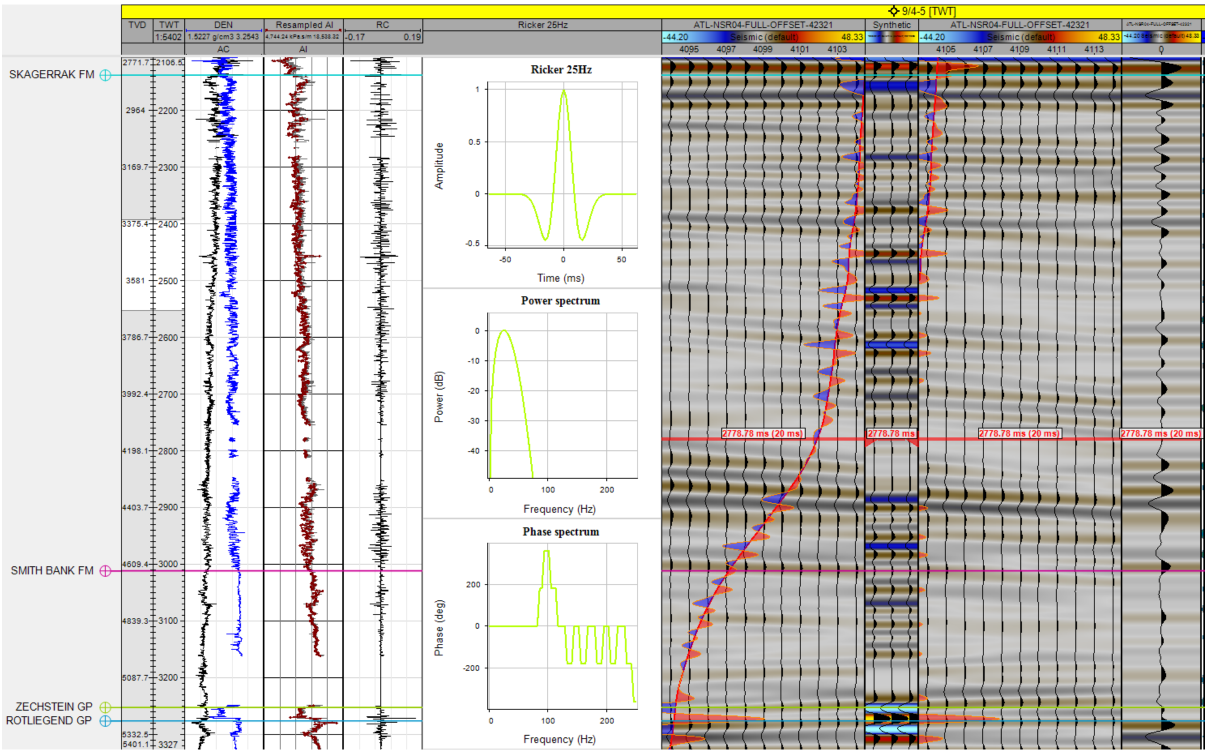


Figure 4-6 Seismic well tie for well 9/4-5 using a simplified Ricker wavelet.

4.3.4.2 Well Log Interpretation

The borehole data utilized for interpretations were dominantly GR log from the different wells. In addition to GR logs, neutron and density logs were also available for interpretations. The GR log was used to define fining or coarsening upwards cycles in the log motif at different scales. The cycles were then used to define lithology and depositional elements within the Triassic succession to be tied up to seismic facies analyses.

4.3.5 Core Studies

Core data were used in this study to calibrate lithology and infer depositional environments of the seismic units. Detailed core interpretations were provided by Aker BP. The reference core used is core 7/12-6 representing the interval for the thesis work, the other cores comprised very short intervals and were not used in depth for the study (table 4-4).

5 RESULTS

5.1 Introduction

The results presented are observed from interpretations done using 2D reflection seismic surveys. They observations presented within the chapter focus on the relationship between Triassic halokinesis and Triassic fluvial deposition.

5.2 Seismic Analysis and Interpretations

Four key horizons were interpreted over the study area in which three are formation tops and one is defined based on the amplitude contrast of seismic facies. Two regional cross-sections were produced across the study area. Figure 5-1 is a northeast-southwest transect illustrating the structural elements in the study area. Figure 5-2 strikes east-west over the central part of the study area. The color legend used in the cross sections is the same as that for the figure selection of the following chapters. The transects in figure 5-1 and 5-2 references the observations and interpretation throughout this chapter. The cross-section show the four key horizons mapped in the seismic data. Intra pod stratal thickness difference observed as wedges are seen on the SW-NE cross-section. The E-W transect show a more equal distribution in thickness and tabular facies. Two main Triassic packages were distinguished from the regional cross-sections. Stratal variabilities are seen over the entire area and in each pod.

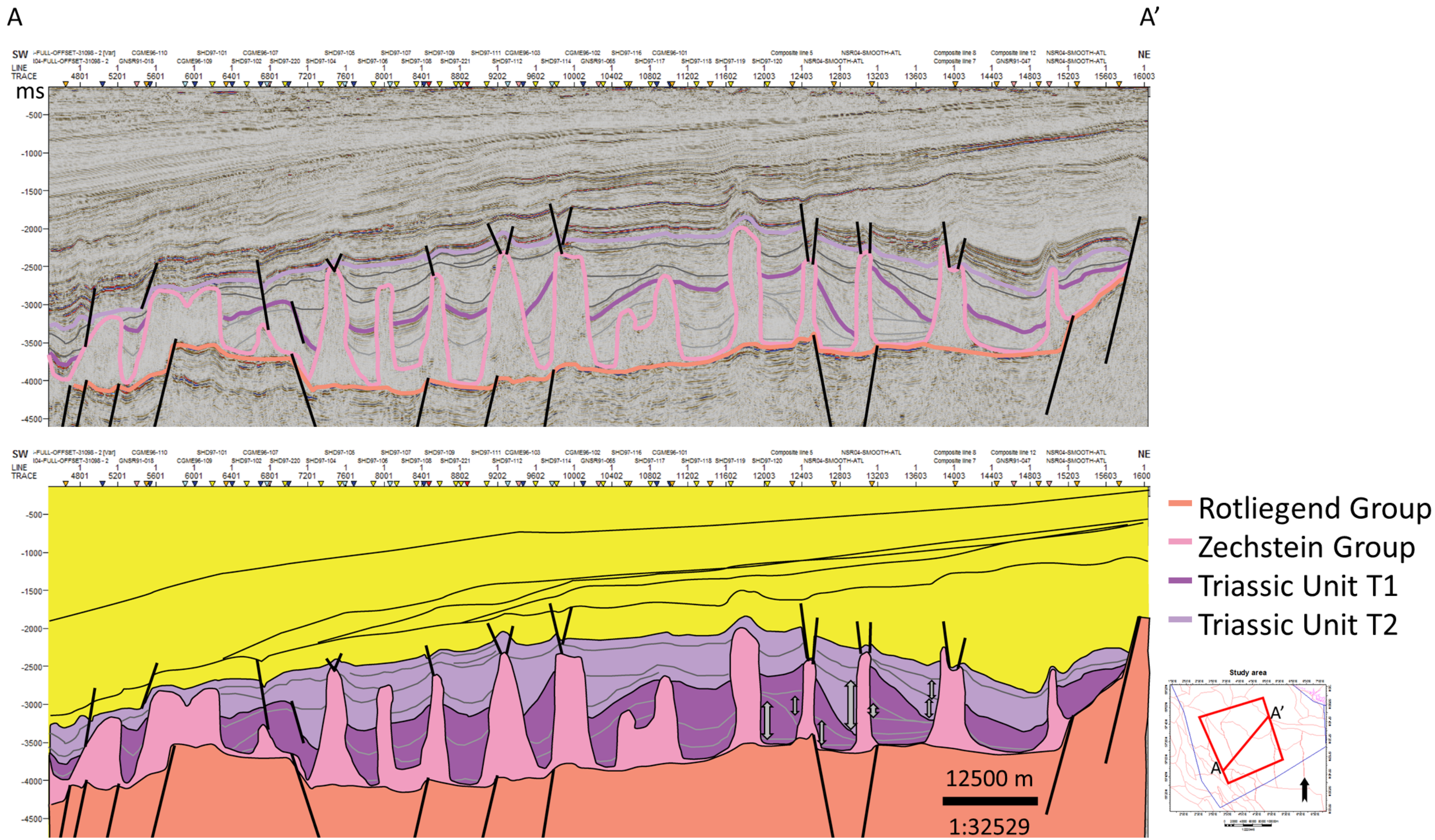


Figure 5-1 Northeast- southwest regional cross-section of the Triassic succession. Arrows indicate different rim syncline evolution.

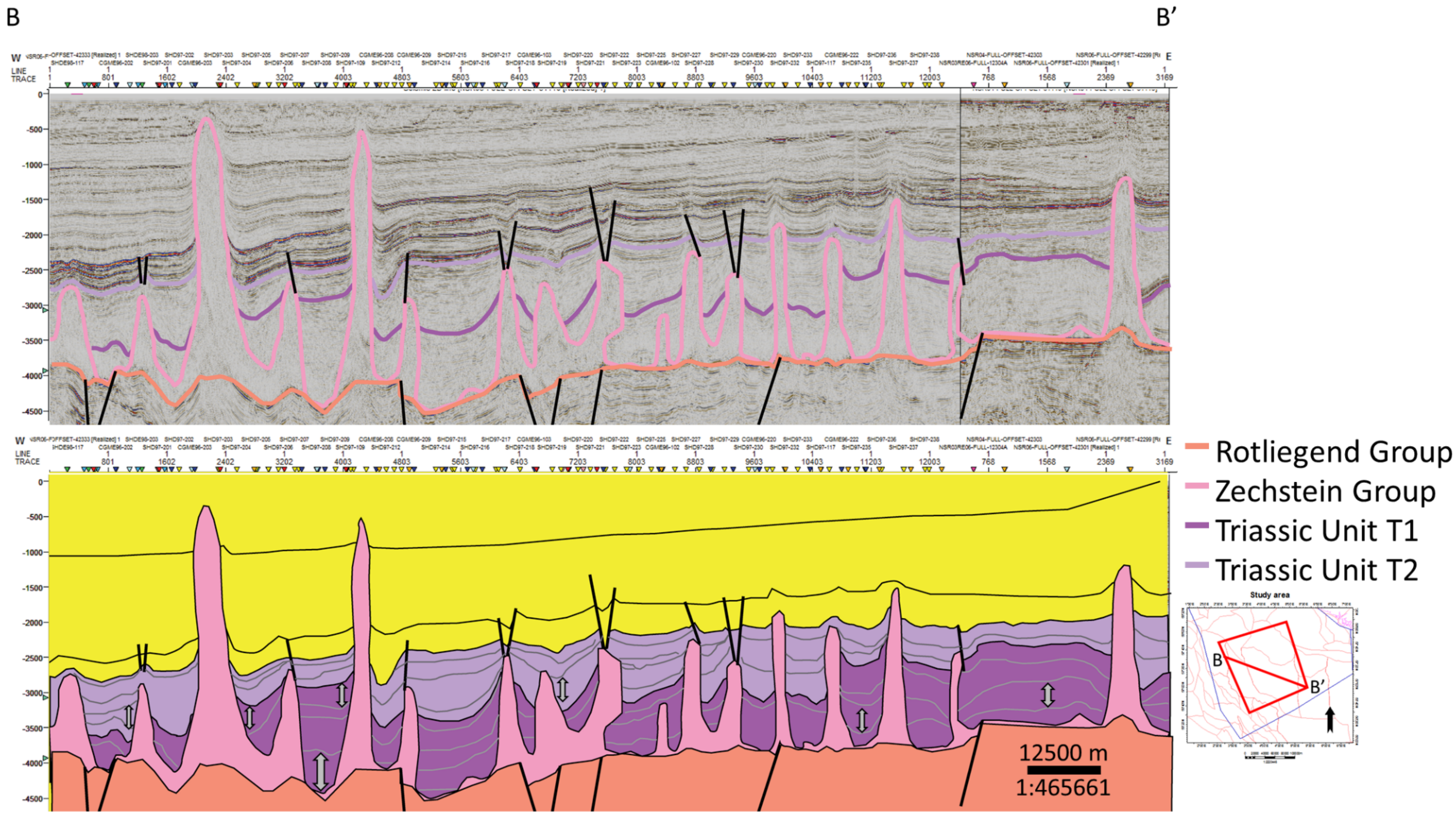


Figure 5-2 Regional cross section striking east-west. Rim synclines are tabular to sub tabular in the central part of the study area.

5.2.1 Rotliegend Group

5.2.1.1 Observations

5.2.1.1.1 Seismic Observations

The reflector defining the top of the Permian Rotliegend Group is a strong positive amplitude reflector and were picked as a peak reflector and characterized as a generally continuous reflector event. Where the Zechstein salt has a diapiric appearance top Rotliegend is distorted and loose continuity. The amplitude strength of the reflector varies but is mostly defined by high to intermediate amplitude contrast. The lower amplitudes of the reflector are situated underneath the salt structures, have close to zero response and are hard to identify on the seismic cross-sections. The horizon is offset by faults that define a graben system with different displacements of the top Rotliegend seismic event. Only minimal stratal variations in the formation thickness are seen on the cross sections and there are no fault related wedges present within the hanging walls of the sub-salt faults (fig 5-1, 5-2). The fault blocks have a tilted appearance seen on the southwest-northeast cross section (fig 5-1) and east-west cross-section (fig 5-2).

5.2.1.1.2 Map Observations

On the surface map in figure 5-3 fault blocks are observed displacing the formation creating a graben system in the central part of the study area, the Åsta Graben, North Permian Basin. In the northeast, a depression is located in the present-day Jurassic Egersund basin. Great displacement is observed in the southwest in the hanging wall of the Coffee Soil Fault Complex. Two fault families are observed from the major fault complexes on the surface map respectively striking north-south and east-west (figure 5-3). The faults in the study area are normal faults and on the surface map, they are represented as fault complexes comprised of several large normal faults.

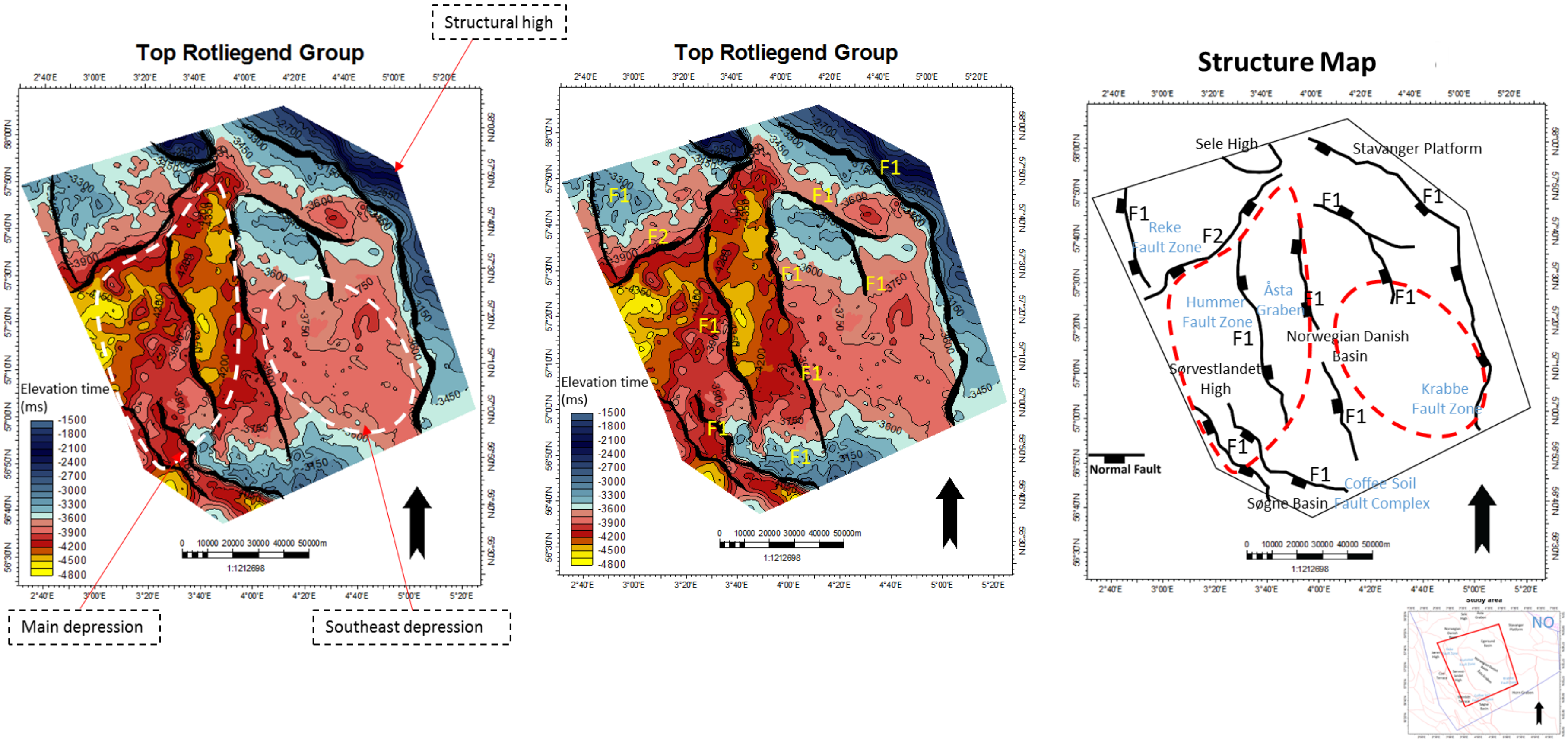


Figure 5-3 Left: Structure map of the Top Rotliegend.Middle: Fault Families of the sub salt faults attached to the surface map. Right: Structure map representing the structural elements and the sub salt faults, it also shows the depressions observed on the surface map to the left.

5.2.1.1.2.1 Fault Family 1- North-South Oriented.

Fault family 1 (F1) comprise faults strikes in a north-south direction and are mostly large basin bounding fault complexes demonstrated by the structure map in figure 5-3. The fault family covers most of the basement faults in the study area. The fault complexes create the sub-salt graben system and are thick skinned normal faults. The fault family comprises the Reke Fault Zone, the Hummer Fault Zone, the Coffee Soil Fault Complex, the Krabbe Fault Zone. The fault complexes are located within the entire study area and the fault complex varies from striking over the entire study area or being located at the margins. The faults dip towards the east and west.

5.2.1.1.2.2 Fault Family 2- East-West Oriented

One fault complex makes up the second fault family (F2). The normal fault complexes strikes west-east. The fault is located in the northwest and bounds the Norwegian Danish basin and the Sørvestlandet High to the Jæren High. The fault is dipping towards the south and constitutes parts of the Reke Fault Zone.

The deepest depression of the Rotliegend Group is located in the hanging wall of the Hummer Fault Zone in fault family F1 in the central area of the study area. The surface reaches a total depth of 4700 milliseconds (ms) (fig. 5-3). The eastern depression reaches a depth around 4000 ms located in the hanging wall of the Krabbe- Fjerritslev Fault Zone. The western margin of the area is located at great depths, these are related to the proto Central Graben faulting as the Coffee Soil Fault in F2, and the Reke Fault Zone in F3.

5.2.1.2 Interpretations

The Rotliegend deposit shows no clear sign of wedging within the data implying that the sub-salt thick skinned faulting was post-Early-Middle Permian. In turn, this implies that the Rotliegend Group is pre-rift deposits. The Top Rotliegend surface defines two main rift depression (fig. 5-3) bounded by fault complexes. The main depression is the Åsta Graben, and the other depression is situated in the hanging wall of the Krabbe Fault Zone in the Norwegian Danish Basin

Three tectonic domains are seen on the Top Rotliegend structure map. These are defined by the underlying graben system.

- Structural high in the eastern study area
- Half graben in the central parts covering the minor depression (fig 5-3)

- Deep graben in the west covering the Åsta Graben, main depression (fig 5-3)

5.2.2 Zechstein Group

5.2.2.1 Observations

5.2.2.1.1 Seismic Observations

The reflector expressed as the top salt is defined as a strong amplitude trough when situated directly above underlying strata or parallel to the horizontal. An abundance of salt structures are seen in the cross-section from figure 5-1 and 5-2. They are characterized by chaotic discontinuous reflectors, which differs from the adjacent more continuous reflectors. The top salt reflector might have a strong amplitude contrast in comparison to the surrounding strata. The Zechstein Group is distributed into several halokinetic bodies that comprise different shapes, sizes and height. From the transects the common geometries are sub- triangular features that varies between narrow, straight features to more triangular structures with and upward thinning trend. A common feature on the salt structures are that the top appear to by relatively flat. The salt flanks are upturned from the base and no evidence of salt overhang is common.

5.2.2.1.2 Map Observations

On the map of top Zechstein (fig. 5-4) a network of salt structures have evolved. The tallest structures penetrating to shallower levels are located in the west and almost pierces up to the seabed. The salt structures in the southern section are more randomly orientated, these shifts orientation between an east-west, south-north and southwest-northeast trend. In the east elongated salt features are observed trending north-south. The distribution and orientation of salt structures are later used to define halokinetic domains.

The isochore map of the Zechstein Group comprises one major depocenter striking from southeast to northwest. In the depocenter, the salt is randomly distributed. Although the salt structures generate a random pattern, a clear trend shows that they are more oriented in a northwest-southeast.

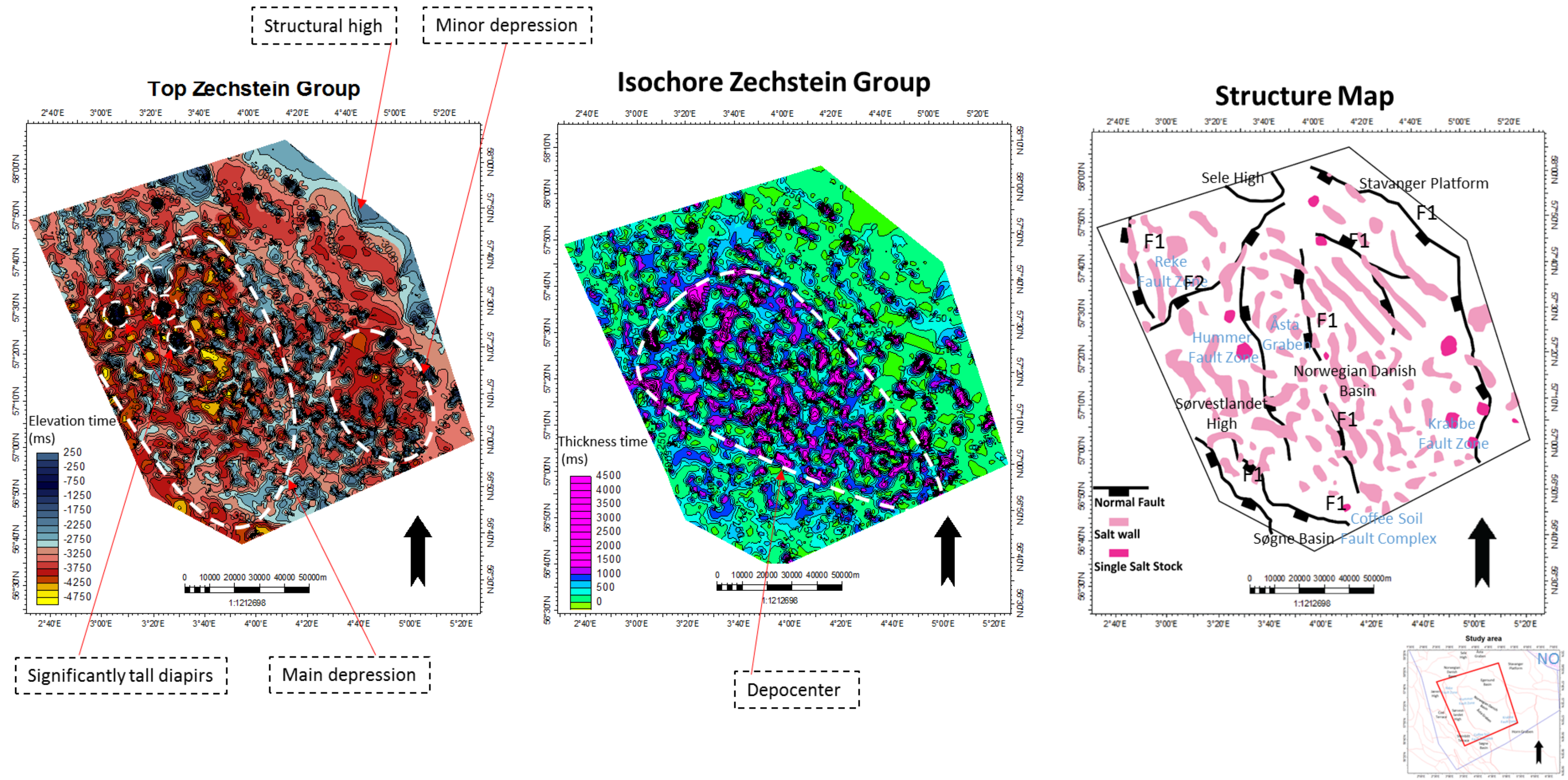


Figure 5-4 Left: Surface map of the Zechstein Group with white circles defining the depressions. Middle: Isochore map of the Zechstein with one well-defined depocenter. Right: Structure map of the Late Permian tectonics present day structure.

5.2.2.1.2.1 Halokinetic Domains

The study area was divided into four domains based on the distribution of salt structure types, orientation and the related pod alignment. The orientation and type of the salt structures are based on the observations of the structure maps (figure 5-4). See section 5.5 for a more thorough explanation of the domains. The halokinetic domains are illustrated in figure 5-5 and the following observations refer to the map in the figure.

- Area A is situated in the northeastern part and comprises elongated salt structures trending northwest to southeast. They are laterally extensive and parallel with respect to one another. The domain is consisting of elongated salt walls.
- Area B includes the deepest local sub-basins and is most abundant in isolated pods. Salt structures are still present but are less extensive compared to Area A and have a more asymmetrical appearance. The domain is consisting of elongated salt walls and significantly tall salt stock on the Sørvestlandet High.
- Area C located in the northwest. The domain encloses shallower pods that are separated by a random distribution of salt walls and diapirs. The salt structures are located on a structural high.
- Area D is located in the southern parts of the study area and include salt walls and diapirs distributed in a random pattern. This area comprises the largest pods surrounded by salt diapirs. The domain is consisting of north-south oriented salt walls, randomly oriented salt walls and salt stocks located in the east close to the Krabbe Fault Zone.

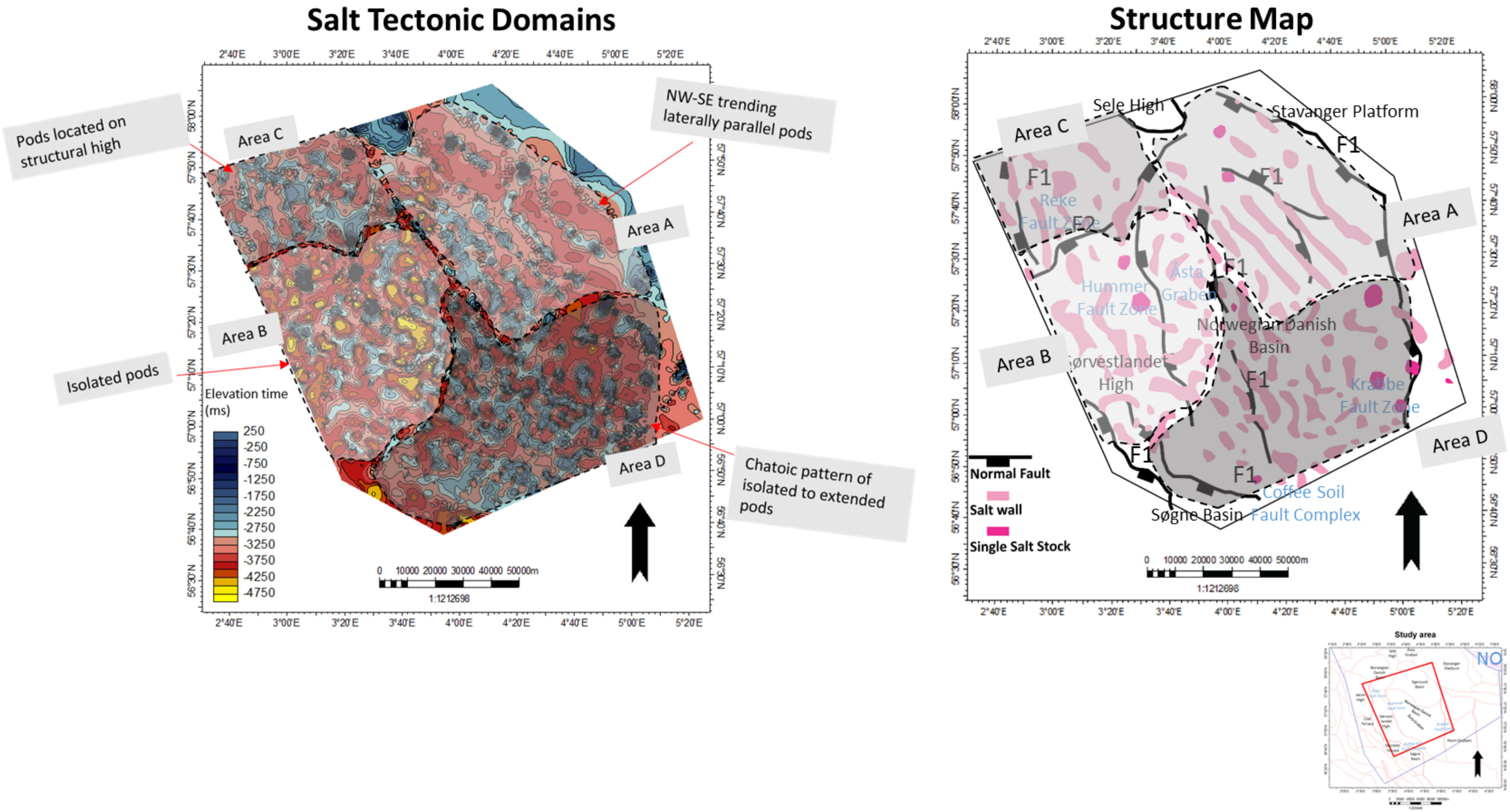


Figure 5-5 Left: halokinetic domains matched with the underlying top Zechstein Group surface. Right: Structure map of the Late Permian structural features and the halokinetic domains.

5.2.2.2 Interpretations

The top of the Zechstein Group defines the distribution of the halokinetic structuring of the study area. The geometry of the salt structures observed from the regional cross sections, surface and thickness maps infer that a few styles are common in the study area. The most common features are salt walls, salt stocks, triangle-shaped diapirs, salt pillows/anticline and collapsed diapirs.

The most common salt structure of the listed is salt walls and singles stocks. The salt stocks are significantly taller than the salt walls i.e. the three tall stocks in area B (fig 5-5). The salt walls are mostly striking south-southeast to north-northwest trend (halokinetic domain area A), which are easier to identify in the eastern and central parts of the area. Otherwise, an abundance of salt walls are asymmetrically oriented and strikes in different directions. The asymmetrical orientation this feature is especially common in the depocenter (see figure 5-4 isochore) and in halokinetic domains B, C and D. In the asymmetrical domains the salt walls appear connected and isolates the adjacent minibasins.

The structure map shows that the salt walls are aligned to the underlying sub-salt basement faults. This is seen in the Egersund Basin (halokinetic domain area A) where the parallel salt walls are trending in the same manner as the underlying faults. In the Regional cross-sections, it is seen that the salt diapirs and walls are often associated with underlying faults(figure 5-1 and 5-2). The cross sections illustrate that Upper Triassic strata overlie most of the salt walls, but some are piercing through the Triassic duvet to later onset reactivations.

5.2.3 Lower Triassic Unit T1

5.2.3.1 Observations

5.2.3.1.1 Seismic Observations

The top reflector is defined as a trough reflector event. The marker can appear as a single strong amplitude reflector, a package of reflectors with amplitude strength increase in center of isolated pods changing to indefinable in other pods. The trend of strong amplitude markers are situated in halokinetic domain area B and in the northern parts of halokinetic domain area A. The general identity of the unit is that the seismic marker is concordant with its overlying and underlying reflectors where present. The unit commonly comprises relatively low to transparent reflector amplitudes.

In the deep part of the unit, the internal reflectors are mostly concordant with the underlying salt deposits. Whereas the shallower reflectors are often tilted and have a wedge appearance. From the NE-SW (fig 5-1) cross-section, wedging is more common in the northeast (Egersund Basin area) than in the southwest. The common feature of the reflector packages within Lower Triassic Unit T1 terminates towards the flanks of the salt structures. The reflector terminations are typically tabular facies. The tabular facies are especially common within the lower and middle part of the unit. Minor intra Triassic faulting displaces the formation locally in sedimentary pods as illustrated in the south-east on figure 5-1. For smaller salt structures, the intra Triassic seismic marker tends to stop on the crest of the diapirs.

5.2.3.1.2 Map Observations

Two major depression are defining the surface of the Lower Triassic Unit T1 as seen on the surface map (figure 5-6). The depressions follow the same trend, striking northwest to southeast. No significant fault complexes are seen on the surface map but there are two supra salt fault complexes on the central part of the area on the flanks of the depressions. The surface map display that salt walls piercing the horizon is common.

Two depocenters are identified on the isochore map in figure 5-6. The eastern depocenter is located in the southeast and strikes northwest terminating at the Sele High. The depocenter is situated in the Egersund Basin bounded by the Stavanger Platform in the east. The depocenter is characterized by elongated pods with good connectivity that are deeper in the south part of the section. The western depocenter is located in the central part of the study area. The depocenter is located across the Åsta Graben and the Sørvestlandet High. The depocenter is characterized by more isolated pods separated by randomly distributed salt walls. The depocenters join at the northern part terminating to the Sele High. The structure map shows that the depocenters are controlled by subsalt faults.

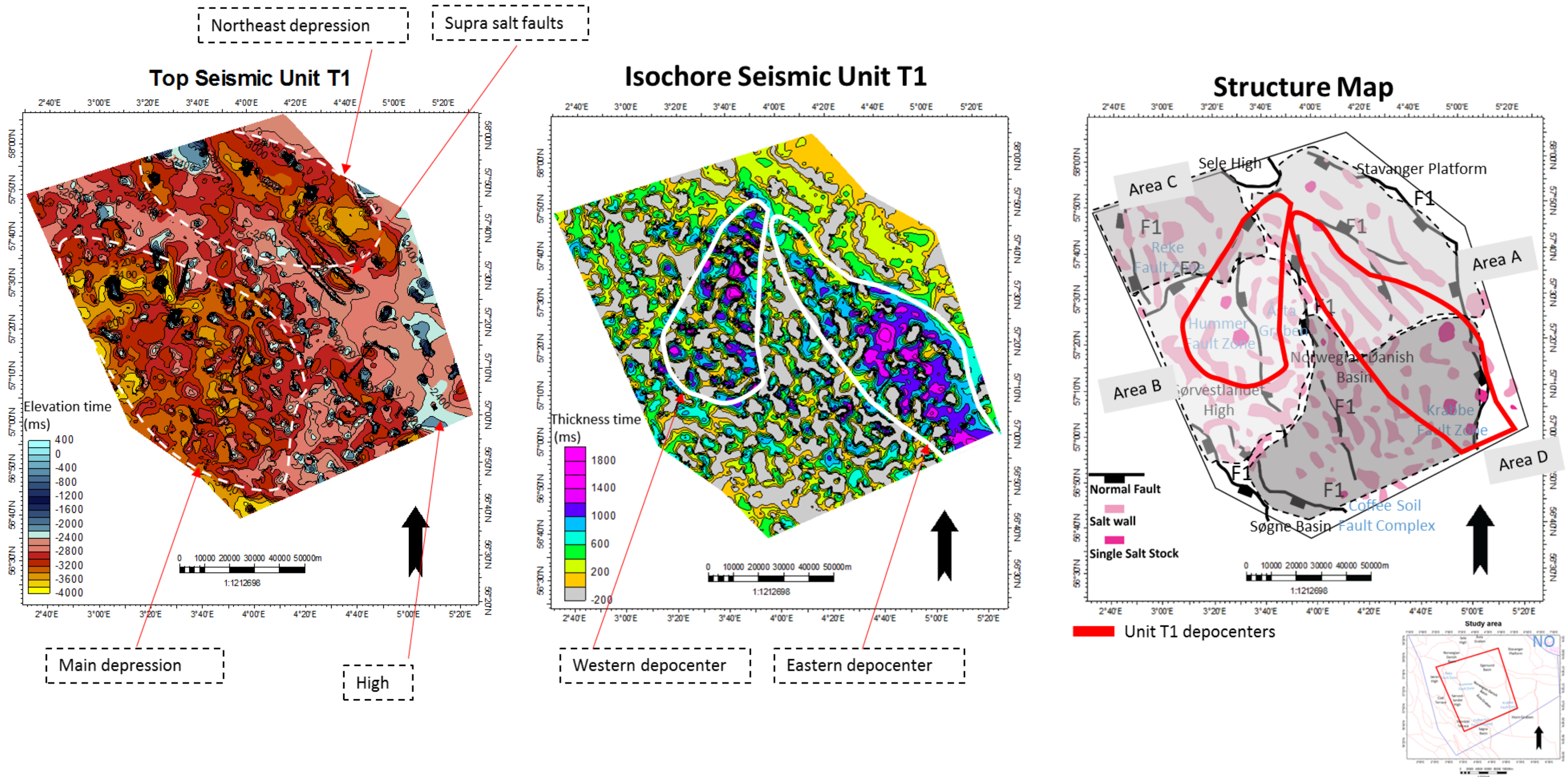


Figure 5-6 Left figure show the top of Lower Triassic Unit T1. Middle: Isochore of Triassic Unit T1 showing to defined depocenters. Right: structure map with the depocenters of Unit T1.

5.2.3.2 Interpretations

The transparency of the reflectors in the unit infer a rather monotonous succession or alternatively less impedance contrast between stratal units. The tabular appearance of the lower reflectors implies that they are deposited uniformly on subsiding salt. Wedges in the pods imply that the halokinetic movement was active locally. These local areas of differential loading possibly reflect on the underlying salt withdrawal. From the cross section in figure 5-1 the early fluvial systems build out in the Egersund Basin in the northeast. The unit is localized in salt wall confined pods, which restrict the lateral extent of the strata.

The strong amplitude reflector defining the top of Lower Triassic Unit T1 implies a lithology change. Although the Lower Triassic Unit T1 is a poorly calibrated, the thick package has been interpreted as thicker floodplains, lacustrine dominated and even marginal marine strata. This suggests a retreat of the fluvial system potentially associated with a climate change. It is noteworthy that this transition also appears to be associated with the onset of increased basin structuring.

The surface map of Lower Triassic Unit T1 indicated that halokinetic basin structuring took place after deposition of the Lower Triassic basin fill period. The isochore map implies two main areas of deposition with sediment influx from the north or northeast. They imply that the early Triassic deposition was focused along the eastern part of the basin

5.2.4 Upper Triassic Unit T2

5.2.4.1 Observations

5.2.4.1.1 Seismic Observations

The top reflector defining the upper boundary of Upper Triassic Unit T2fluctuates between a strong positive amplitude to almost zero amplitude contrast. The top boundary reflector also alternate from appearing as a chaotic discontinuous to a more continuous reflector (figure 5-1 and 5-2). The Upper Triassic Unit T2 is characterized by high amplitudes and have improved reflector coherency. A strong amplitude reflector was defined as the base of the unit.

The internal pod geometry of Upper Triassic Unit T2 comprises parallel beds and wedges. Wedges are more common at the lower parts of Unit T2, whereas the tabular to semi-tabular facies are more common in the upper parts of the succession. Commonly the lower parts of the unit onlap onto the basal surface. The upper parts of Unit T2 overlie most of the salt structures.

Faulting is mostly present at the uppermost part of Unit T2 as supra salt fault deformation. Some cases of intra pod faulting displace the unit (fig 5-1). Most faults are however of post-Triassic origin. The cross sections (fig. 5-1 and 5-2) show that not all sedimentary pods have grounded onto the underlying Rotliegend basin having depleted the Zechstein deposit. They are restricted to certain areas within the dataset (see next section).

5.2.4.1.2 Map Observations

The surface map generated from the top Skagerrak Formation displays a generally smooth surface overtopping the Zechstein salt structures with two deep depressions (fig. 5-7). The main depression covers the western flank of the study area, in this area, three tall salt stocks pierce the Triassic strata. The minor depression is situated in the Egersund Basin. The depression also comprises salt walls piercing the top of Unit T2 situated in the central part of the basin. The basins connect in the northern part south of the Sele High.

The isochore map (fig. 5-7) display two depocenters. The main depocenter strikes southeast to northwest and terminates onto the western flank of the study area. The depocenter cuts across the Norwegian Danish Basin, the Åsta Graben and onto the Sørvestlandet High. One smaller depocenter is located in the Egersund Basin. The minor depocenter strikes from north to south. In comparison to the Lower Triassic Unit T1 depocenter, the depocenters seen on the isochore in figure 5-7 have shifted westward expanding out from the underlying depocenters.

Figure 5-8 illustrated areas where the trend of sedimentary pods that not grounded is situated (i.e. salt is still present underneath) and are termed floating pods. They are restricted in the western part of the study area and covers the halokinetic domains area B, area C and area D. The trend mapped in figure 5-8 illustrates the main trend of floating pods, the trend also comprises grounded pods as it is a local feature. The floating pods are commonly associated with salt walls situated on sub-salt basement faults.

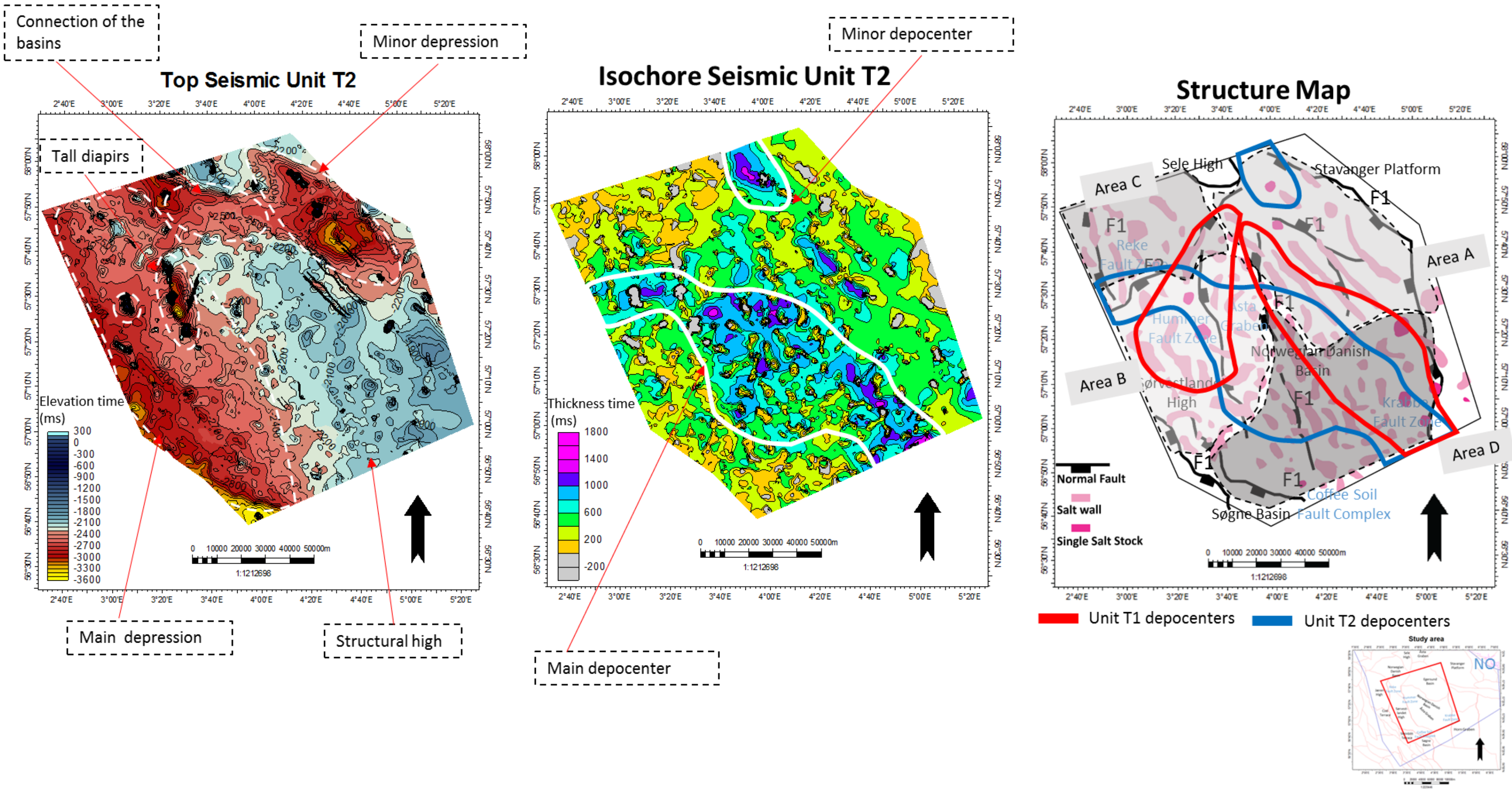


Figure 5-7 Left figure show the top of Upper Triassic Unit T2. Middle: Isochore of Triassic Unit T2 showing one main depocenter and one smaller. Right: structure map with the depocenters of Unit T1 and Unit T2..

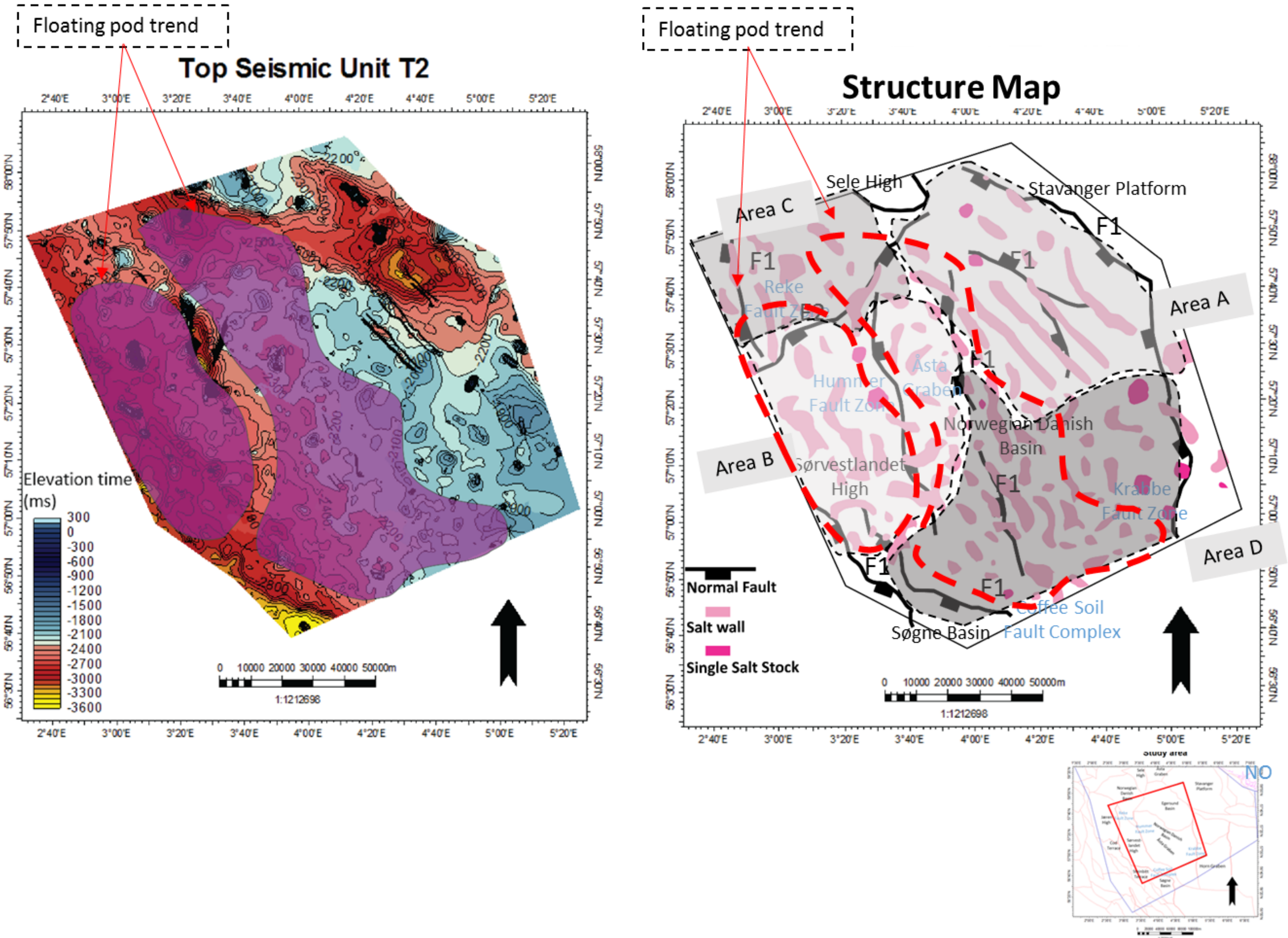


Figure 5-8 A trend of not grounded pods were mapped in the seismic cross-sections. They are located on the west side of the study area (left). On the structure map (right) they are bounded by basement faults.

5.2.4.2 Interpretations

The change from the strong amplitude reflector to weaker amplitude contrast in the Upper Triassic Unit T2 infer that the lithology change. The wedges in the lower parts of the unit indicate that halokinetic and fluvial dispersal was active. Three main levels of fluvial evolution are seen in cross sections, i.e. on figure 5-13. The lowest level imply syn halokinetic deposition, which is indicated by wedges in the rim synclines. The middle level was deposited at the later halokinetic evolution and transition into a less subsiding deposition. The upper fluvial level overtops the salt structures and was deposited after the halokinetic basin structuring. Wedging are common overall within the rim synclines (fig 5-1 and 5-2).

The horizontal bedding covering the salt structures imply that the channel belts extended over the salt diapirs, outreaching the accommodation space. The supra salt faults are thin-skinned minor faults displacing the Triassic –Post Triassic deposits. The faults imply post-Triassic extension in Late Jurassic. The Late Jurassic rifting reactivated the salt structures in the area creating supra salt anticlines bending the late deposits of Triassic Unit T2.

The maps imply that the depocenters of Unit T2 follow some of the same trends and shifts westwards with respect to Lower Triassic Unit T1. The major depocenter crosses the underlying depocenters. They imply that sediment influx now also was dominating on the basin flanks and not restricted to one area as the Lower Triassic Unit T1.

The floating pod trend infers that not all salt have been evacuated from underneath the sedimentary pods. They are often associated with salt walls and may infer that they are intra pods that have subsided to great depths. It may also imply different Zechstein lithology and not pure halite.

5.3 Well and Core Analysis

5.3.1 Well log Interpretations

Well analysis was done on wells that comprise the Skagerrak formation as a criterion. Most wells are drilled adjacent to or onto salt structures which compromises the well control of the Triassic deposits. As well as they rarely penetrate the entire succession if not drilled onto a salt structure. Well logs in this thesis were applied for formation and lithology control on the seismic to calibrate the content of the Triassic units and to tie the wells to the seismic for proper formation interpretation. The GR logs of Triassic strata are mostly low to intermediate API reading with high GR peaks recognized in the logs shown on figure 5-9. Well 9/4-5 was drilled through a pod and represents entire succession evolution providing a large scale view of the depositional environment. Well 7/12-6, on the other hand, are drilled onto a salt wall and provides a more detailed log interpretation of the Skagerrak Formation

The GR log motif corresponds to the two defined seismic units, Lower Triassic Unit T1 and Upper Triassic Unit T2. The boundary between the two seismic units is correlated to the boundary between the Smith Bank Formation and the Skagerrak Formation. The all-over motif of the megasequences is that both units coarse upwards as seen on well 9/4-5 (fig 5-9). The general GR motif of the Lower Triassic Unit T1 is aggrading to blocky and the Upper Triassic Unit T2 have a general coarsening and fining upwards trend.

The observed lithology of the Lower Triassic Unit T1 is monotonous and corresponds to silt and shale. The log motifs seen for the Lower Triassic Unit T1 in figure 5-9 and figure 5-10 by McKie (2014) are interpreted as floodplains and playas.

The lithology of the Upper Triassic Unit T2 fluctuates from being sand prone and mudprone. This is represented by fining and coarsening upwards motifs in the log seen on figure 5-9. The well log interpretations describe a fluvial dominated environment with deposition of fluvial sandstones and playa muds in the Norwegian North Sea seen on the well log correlation in figure 5-10 (McKie, 2014). The correlation implies that the fluvial systems are terminal rivers/ splays into playa systems.

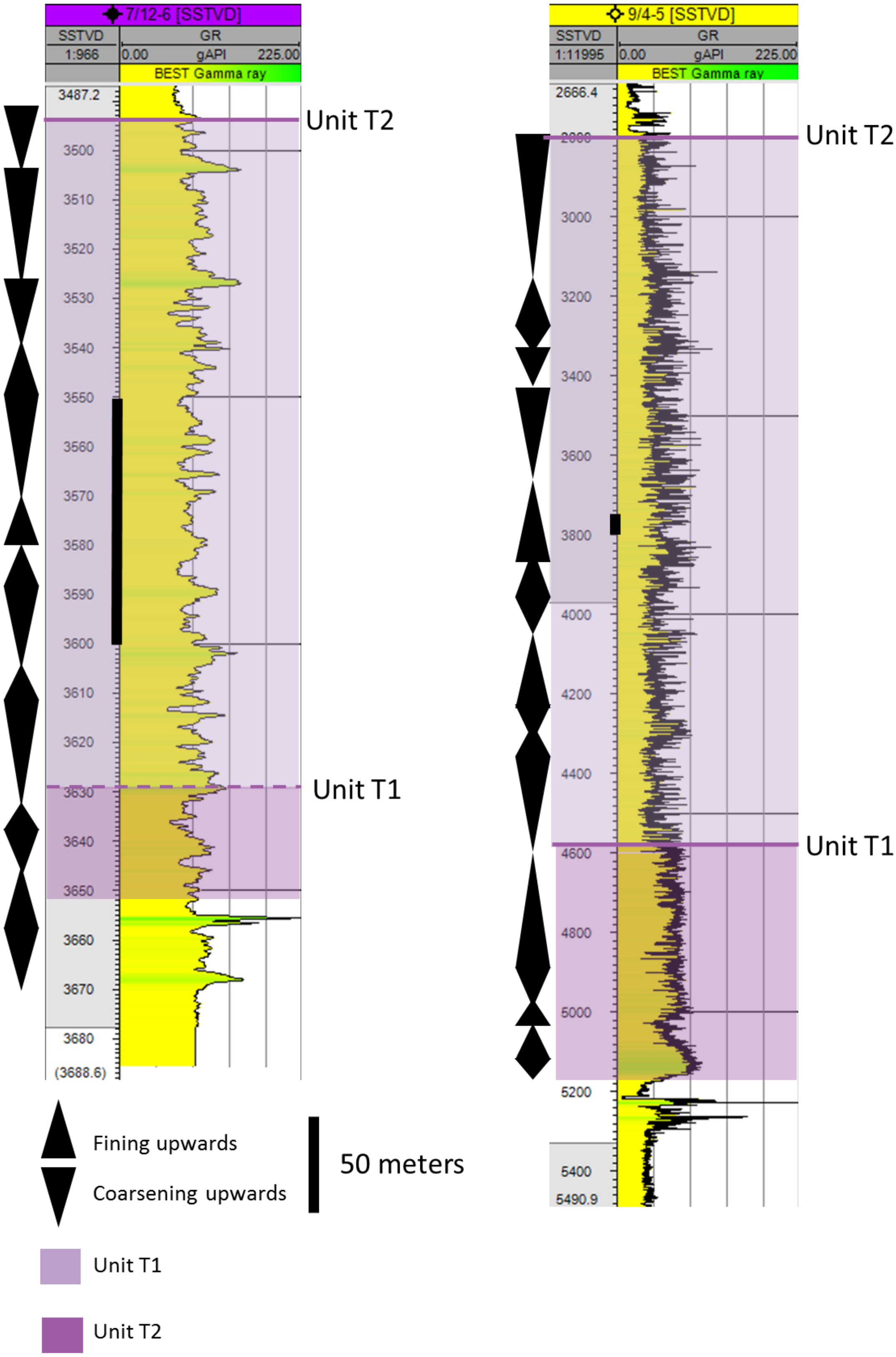


Figure 5-9 Interpretation off well 7/12-6 (left) and 9/4-5 (right). Well 7/12-6 provides a more detailed interpretation, whereas well 9/4-5 indicates the large scale setting.

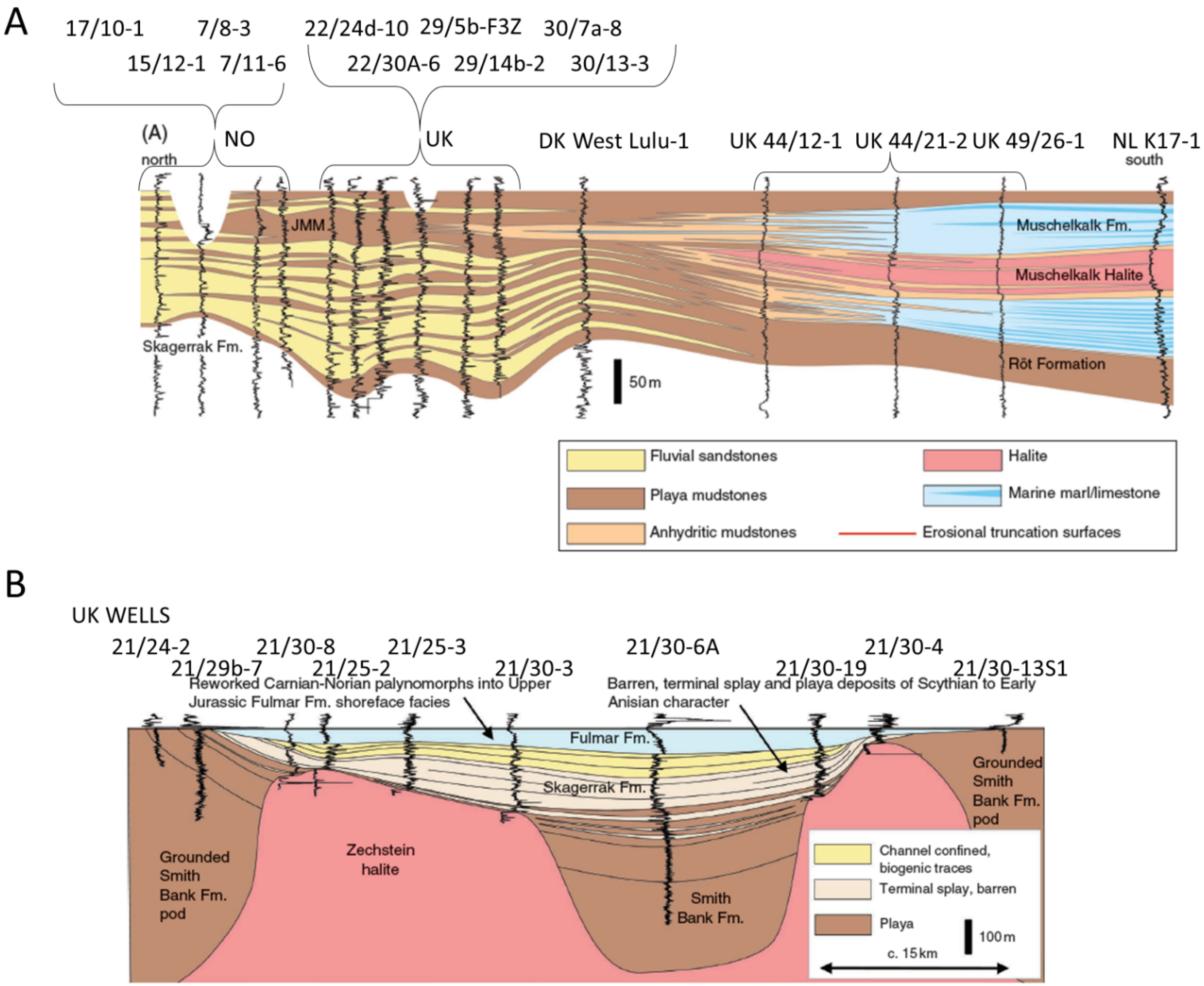


Figure 5-10 A regional well correlation of the Skagerrak Formation from north to south transecting both NCS, UKCS, Denmark and onshore Netherlands. B) A local well correlation from the UK sector of both the Smtih Bank and Skagerrak Formation between the pods . Both well correlations are from McKie (2014)

5.3.2 Core Data Interpretations

The interpretations from the core analysis were provided by Aker BP. For full core analysis see appendix 1. Figure 5-11 display two intervals of the core, core 9 and core 7. The cores display different lithologies of the Skagerrak Formation, The core was generally sand prone. The base of the core (fig 5-18) comprises an interval of shale at the base of the core in core 9. Core 7 from fig 5-18 display repeated channels. The channels base is located at the begging of the cored interval.

The depositional environment at the base is representative of an arid continent with rapid evaporation of channels. This is seen from the channel base and shallow early channel development at 3634-3632 meters. A column of shale deposits is seen on core 9 in figure 5-11. The shale column follows the deposition of an early fluvial channel development that was evaporated rapidly.

In the shallower interval from the core in figure 5-11, the depositional environment is interpreted as a fluvial system. The surrounding environment was still dry but with a more humid profile, seen from the fining upwards profile of the fluvial channels. The channels fluctuate between high and low sinuosity rivers. The sinuosity indicates that the climate was more humid in the Upper Triassic Unit T2 than in the Lower Triassic Unit T1.

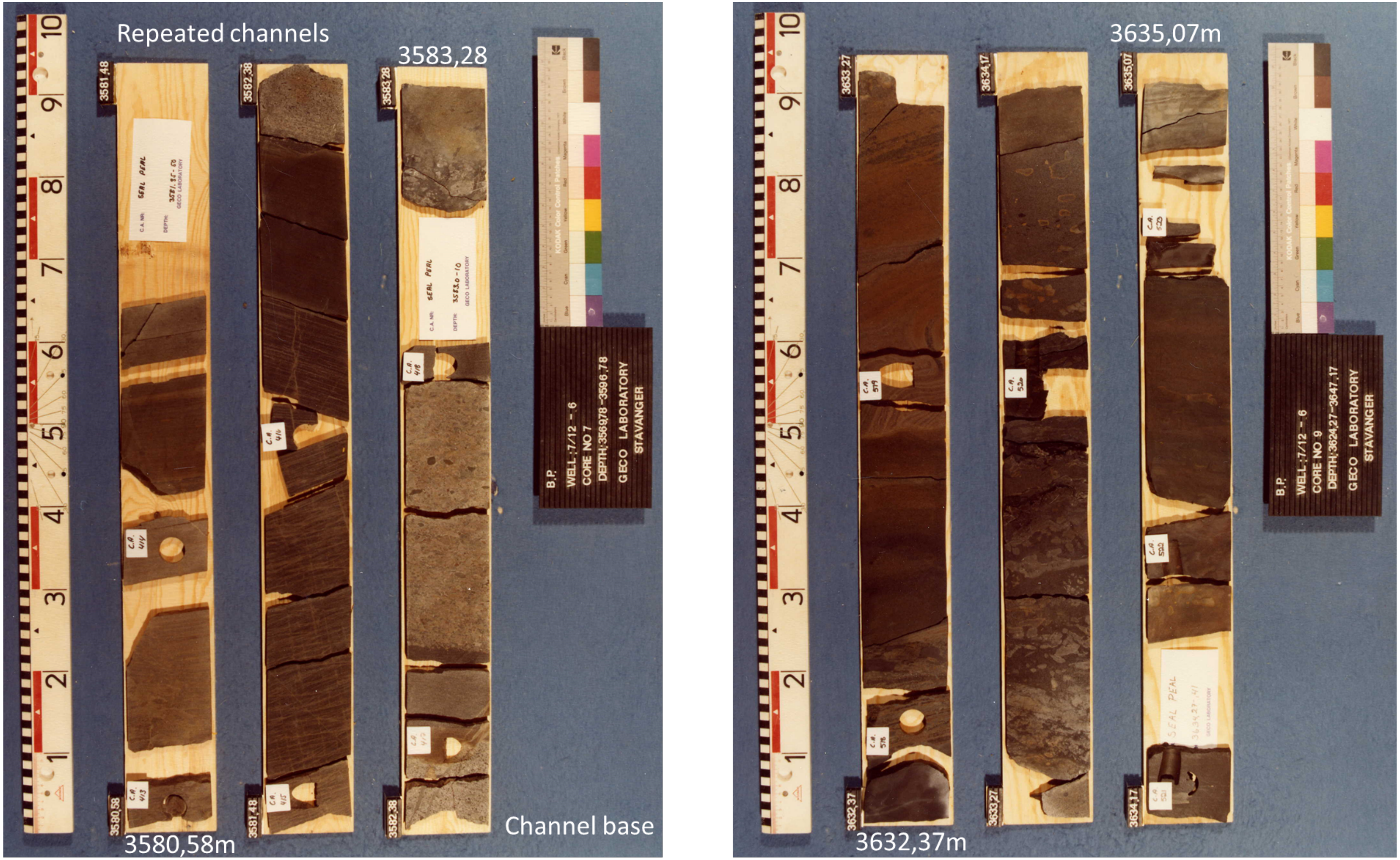


Figure 5-11 Sections from Well 7/12-6. To the left: core 7. To the right at greater depths: core 9. Modified from ((NPD), 2019d)

5.3.3 Seismic Lithology Calibration

From the interpreted well and core data, the Triassic depositional environment can be applied to the defined seismic units. The seismic interpretation of the Lower Triassic Unit T1 (fig 5-12) coincide with the monotonous floodplain or playa deposits interpreted from the well logs and well correlations. The Lower Triassic Unit T1 also comprise sands from terminal splays.

The shale columns interpreted from the core in figure 5-11 and the shale intervals subdividing the Triassic unit can be correlated to the seismic high amplitude reflector. The correlation can be seen in figure 5-13. Shale deposition is also noticeable in the core data, as seen on 7/12-6 located at around 3630 meters (fig 5-11 and 5-13). The flooding may correspond to the Middle Triassic Muschelkalk flooding suggested by Mckie and Williams (2009). Figure 5-13 suggest that the GR peak, the high amplitude reflector and a shale deposit from the core are possible to correlate. This imply that the amplitude contrast in the seismic data (Middle Triassic) corresponds to the suggested flooding from McKie and Williams (2009), albeit depositing shale and not carbonates as expected.

The Upper Triassic Unit T2 correspond to the fluvial environment interpreted from the core, the well log interpretation and the well correlation from (McKie, 2014). The channels are multistorey and multilateral with clearly defined channel bases and a fining upwards motif. In figure 5-12 the amplitude contrast increase in the Upper Triassic Unit T2 corresponding to the more fluctuating log motif of the Upper Triassic Unit T1 in well 9/4-5.

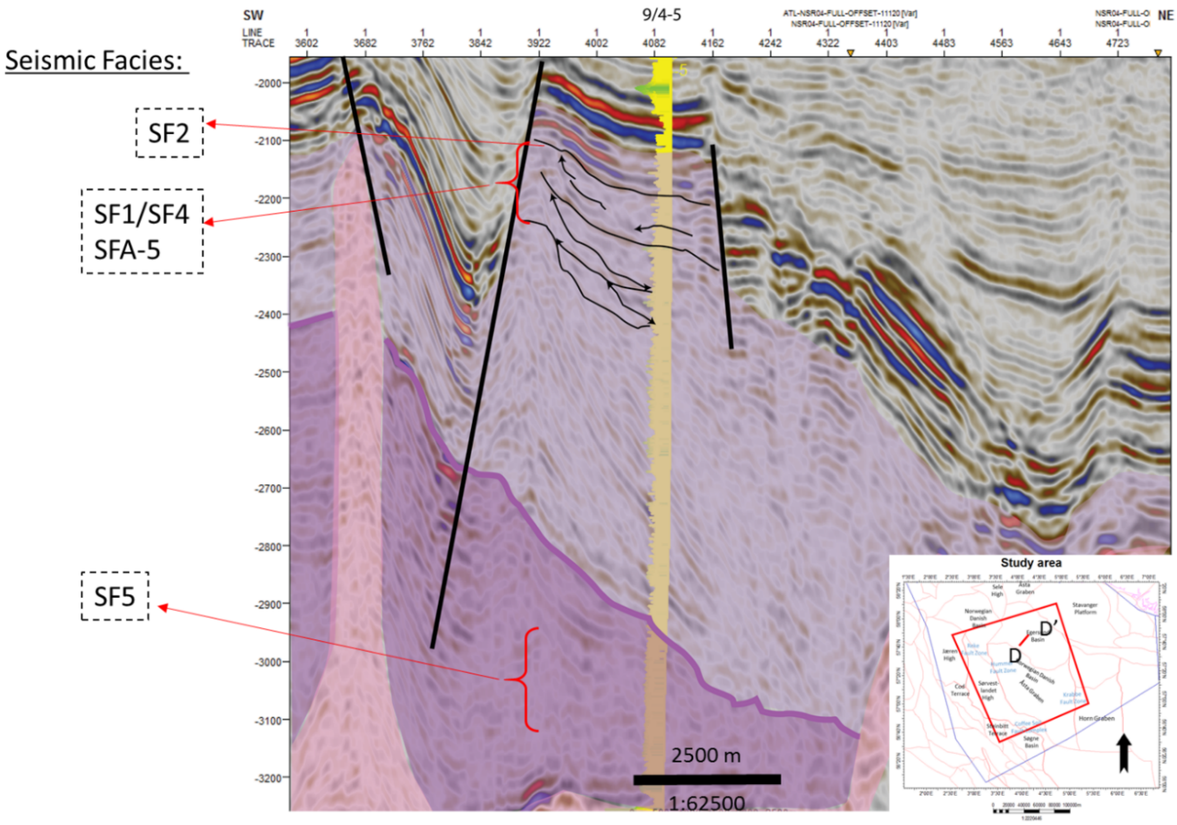


Figure 5-12 Well and seismic correlation of with well 9/4-5, which are drilled through the entire succession the amplitude changes of the seismic corresponds to the log motif.

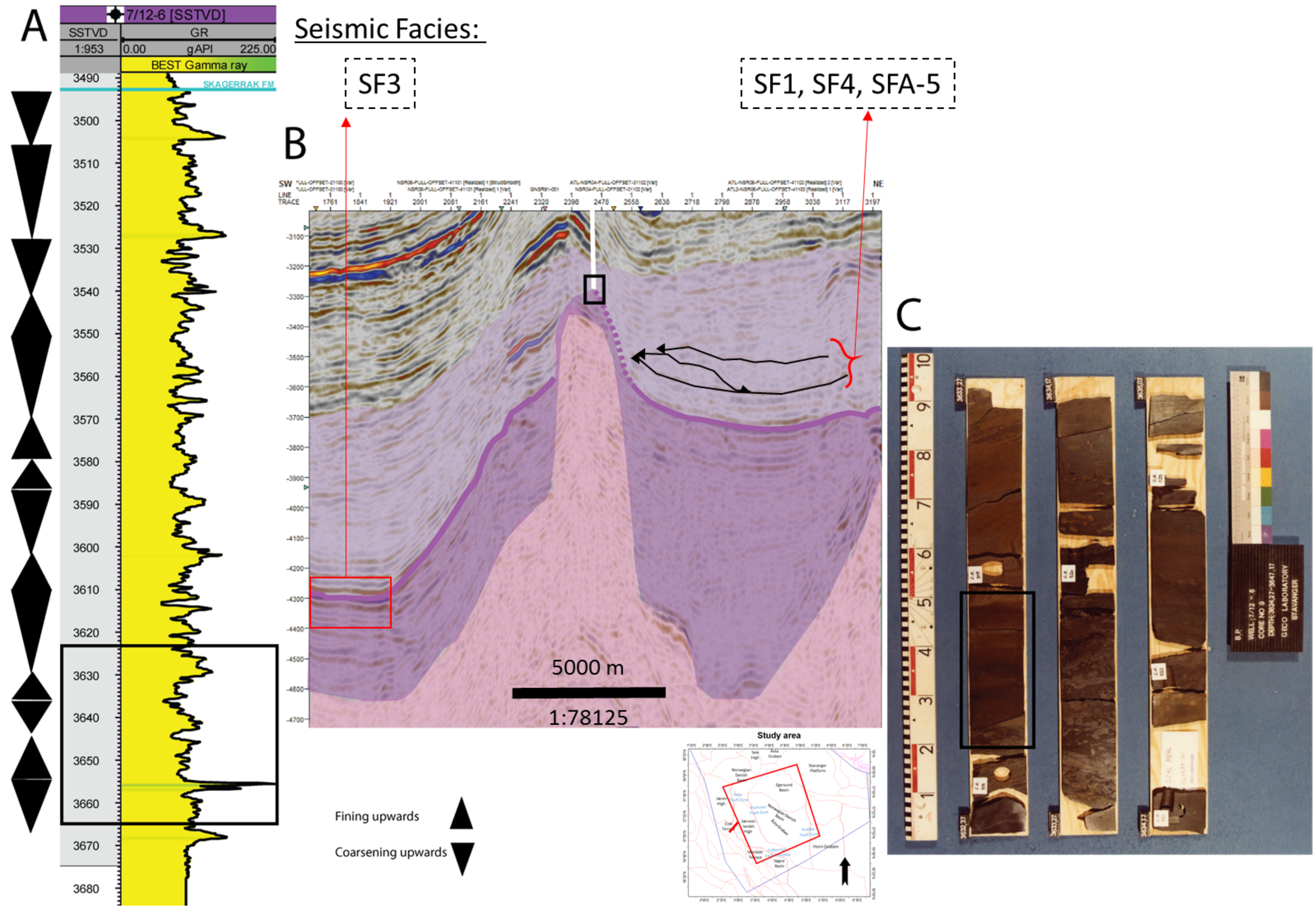


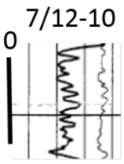
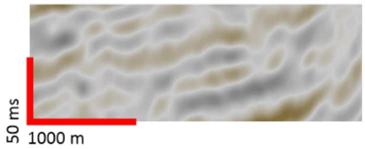
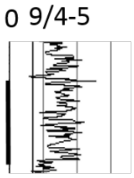
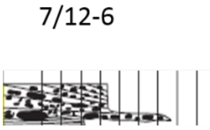
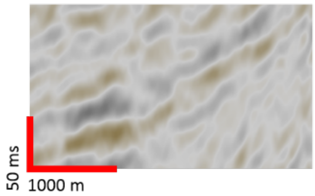
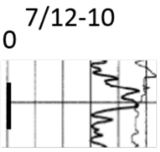
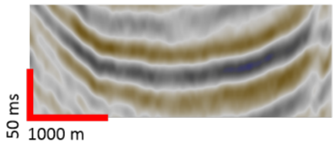
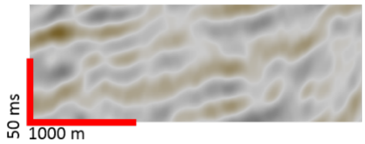
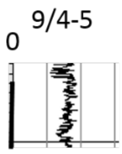
Figure 5-13 Correlation of the High GR log spike, the strong amplitude reflector and the shale column from the core interval. Corresponds to the Middle Triassic boundary.

5.4 Seismic Character

5.4.1 Seismic Facies

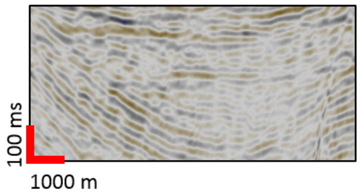
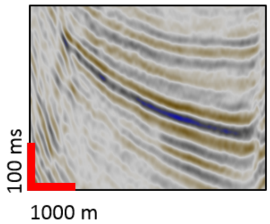
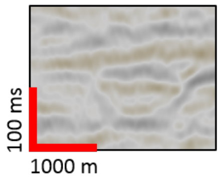
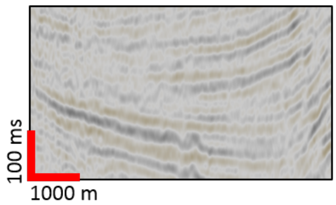
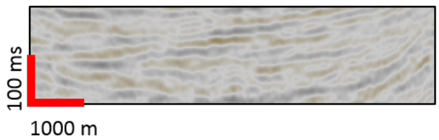
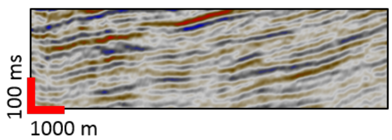
Seismic facies and facies association are summarized and listed in the tables below (table 5- 1 and 5-2).

Table 5-1 Comprise the seismic facies common in the succession.

Seismic Facies	Observation	Interpretation	Log response	Core	Seismic evidence
SF1	Discontinuous low amplitude reflector	Inter channel bar			
SF2	Continuous low amplitude reflector	Sheet like architecture broad multilateral channel complex			
SF3	Strong amplitude continuous, parallel reflectors	Floodplain with alternating lithofacies		No core	
SF4	Wavy reflector , discontinuous, low amplitude	Channel bar	No log		
SF5	Very low amplitude transparent reflector	Silt/shale dominated floodplain. Monotnous lithology		No core	

60 meters

Table 5-2 Seismic facies association. Most of the facies associations indicate a fluvial depositional environment.

Seismic Facies Association number	Observation	Interpretation	Seismic evidence
SFA-1	Onlapping reflectors	Potential stack and laterally extensive channels	
SFA-2	High amplitude package reflectors	Fine grained lithology, floodplain, lacustrine and marine	
SFA-3	Incision into lower reflector. Abrupt reflector terminations	Multistorey channels in incised valley fill	
SFA-4	Wedge thickening towards salt Internal chaos diverging	Fluvial channel deposits or floodplain, lacustrine.	
SFA-5	Divergent to onlapping fill Weak/shallow incisions	Fluvial channel deposits	
SFA-6	Downlap/onlap of reflectors. Dispersion of reflectors.	Laterally extensive channel belt	

5.4.1.1 Observations

The seismic facies and facies associations are listed in table 5-1 and 5-2. The general trend of the observed seismic facies are weak amplitude reflectors of both continuous and discontinuous appearance. Onlaps and downlaps are commonly seen adjacent to the salt structures onto continuous reflectors. Offlapping and dispersal are also a regular feature in the seismic facies and facies associations. The high amplitude events are often bounded by parallel to semi-parallel overlying and underlying reflectors.

5.4.1.2 Interpretations

The seismic resolution introduced in the methodology chapter implies that channel facies and facies associations are interpreted as channel belt complexes. The general interpretation of the seismic facies and facies association are summarized in figure 5-12, 5-13 and 5-14 with mapped facies in the cross section from area D. The Lower Triassic Unit T1 comprises shallow incision facies interpreted as channel belts in surrounding floodplains. The Upper Triassic Unit T2, on the other hand, have distinct seismic facies recognized and figure 5-14 display three levels of fluvial energies in the study area of different impact. The observations imply channel belts deposited in rim synclines at the lower levels (SFA-5) with multistorey connection. Poorly connected channel fills seen in SF1, SFA-1, SFA-5 and SFA-6 from table 5-1 and 5-2 mostly define the fluvial channel belts interpreted on the cross sections (figure 5-12, 5-13 and 5-14).

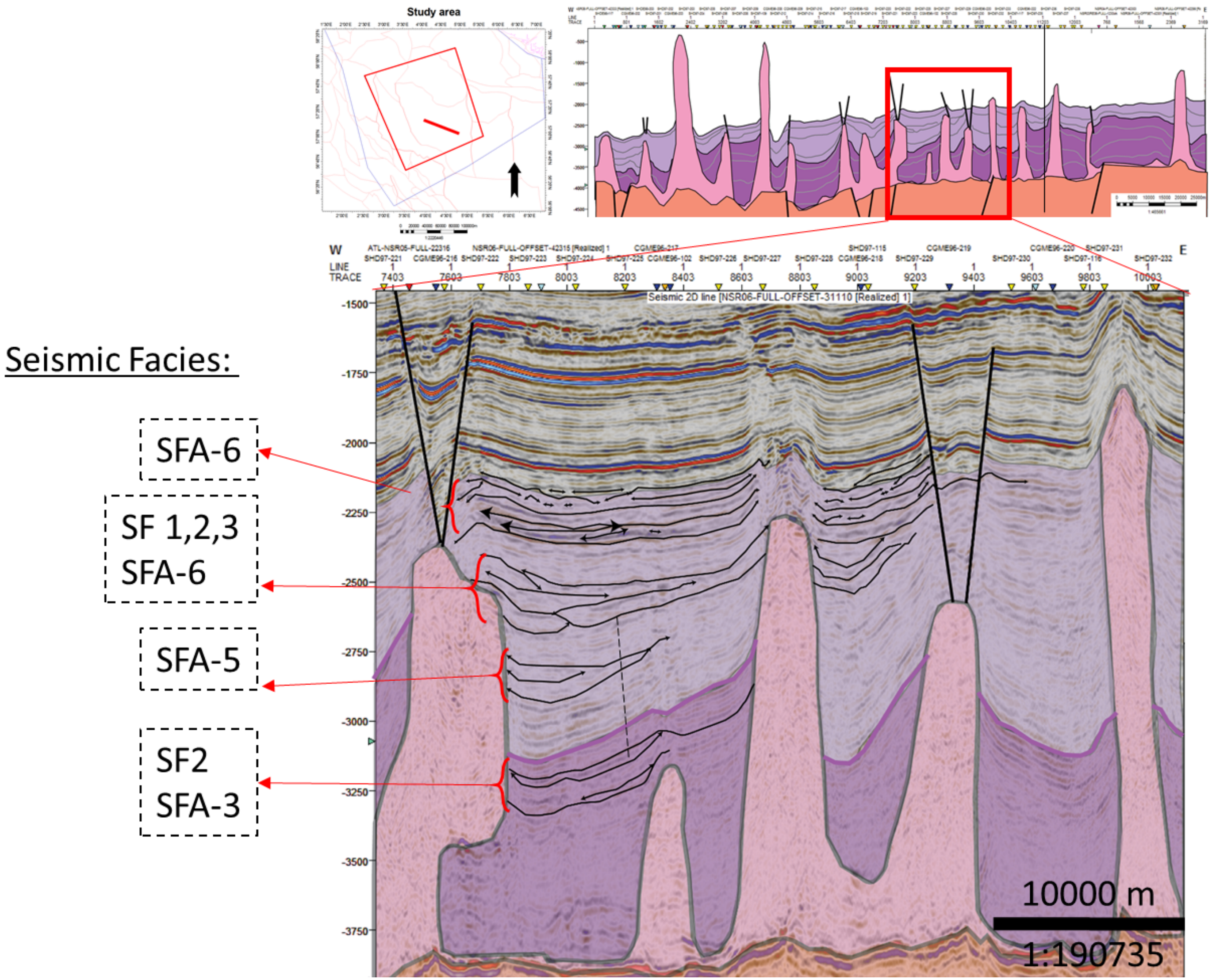


Figure 5-14 Seismic facies and facies associations interpreted on the transect in the Norwegian Danish Basin. A clear change in fluvial trend are observed in the Upper Triassic Unit T2 from a multistorey stacking to multilateral and multistorey stacking..

5.4.2 Amplitude Extracts

5.4.2.1 Observations

The general amplitude response of the reflectors is weak for the entire target succession. The salt structures are dominated by very low amplitude reflections bounded by a strong amplitude through at the base where the salt is vacant and sediments have grounded the thin salt layer is marked by a top strong amplitude trough reflector. Some salt structures also have a defined top marked by strong amplitude reflectors but this amplitude is a rarely occurring feature.

The Triassic packages comprise significantly low amplitude contrast and continuity. A strong amplitude trough (SF3, SFA-2) marks the top boundary of Lower Triassic Unit T1 (fig. 5-15). This reflector amplitude fluctuates, have different amplitude response throughout the dataset covering the study area and are not identifiable in some areas. Top Upper Triassic Unit T2 amplitude response does not hold a specific character and fluctuate from being a strong peak to a weak peak reflector. The package thus comprises a higher amplitude response than the underlying reflectors of T1. The weakest amplitudes are found at the base Triassic deposits where the pods have grounded on the Rotliegend Group deposits (SF5).

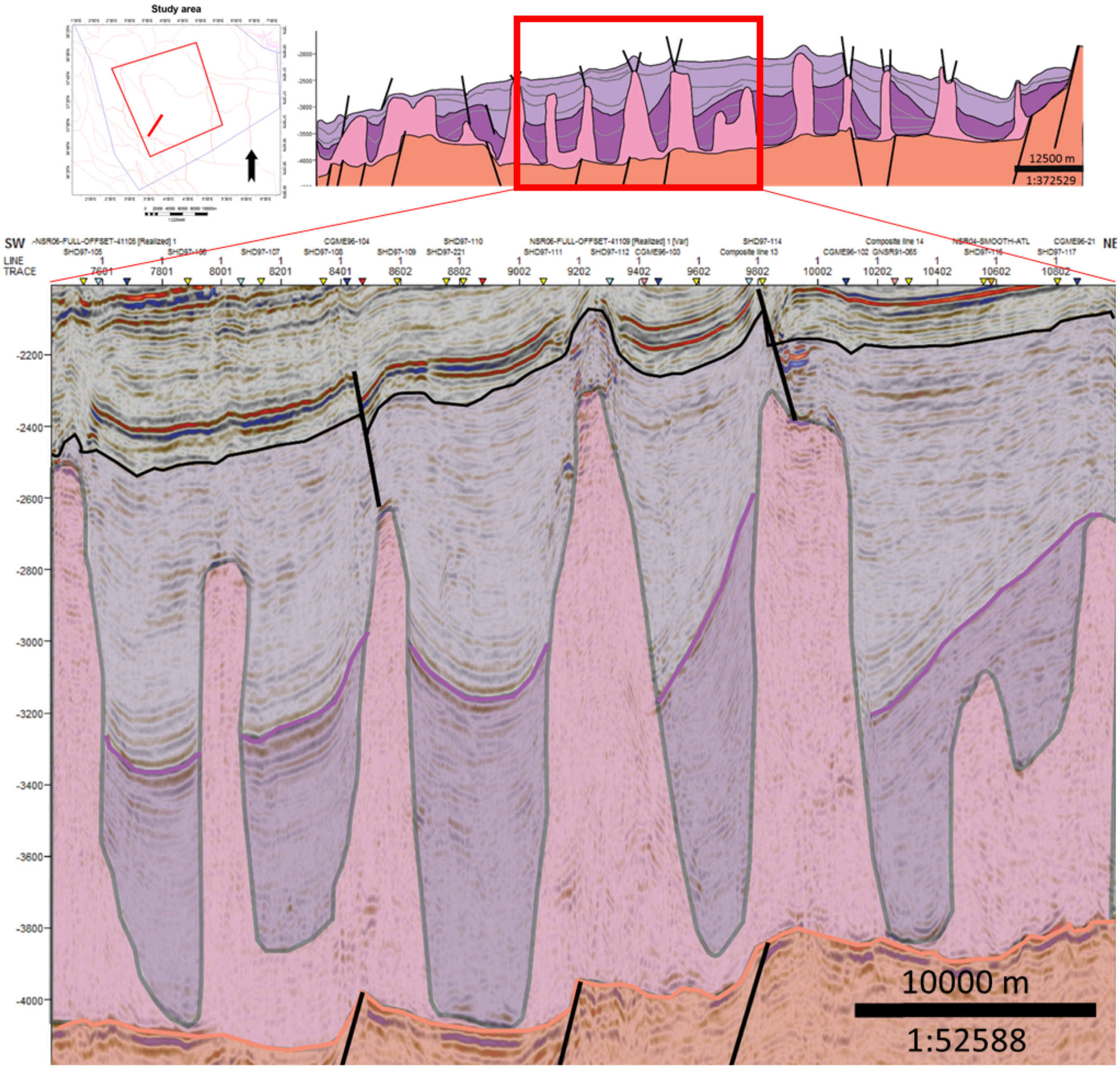


Figure 5-15 Amplitude variations seen in the dataset. The Lower Triassic Unit T1 are weak to transparent. The strong amplitude reflector have a different appearance in the pods and the Upper Triassic Unit T2 are characterized by weak amplitudes.

5.4.2.2 Interpretations

The amplitude difference in the packages responds to changes in the depositional setting. The low to transparent amplitudes of Lower Triassic Unit T1 imply a monotonous depositional environment dominated by floodplain deposits and occasional pluvial streams. The middle Triassic, the boundary between Unit T1 and Unit T2, infer a change in the deposition, which creates an amplitude contrast to the Triassic Units (fig 5-145. Figure 5-15 also show that there is a gradual change in the environment as the amplitude contrast increases down to the boundary and decreases with depth below. The Upper Triassic Unit T2 has greater amplitude contrast than Lower Triassic Unit T1 but still has a weak appearance. This indicates that the environment fluctuated more than in the more monotonous Lower Triassic Unit T1. Seen on the section (fig 5-15) the amplitudes increase upwards in the package and more lithological contrast are present in the succession.

5.5 Triassic Tectonostratigraphic Domain Descriptions

The halokinetic domains were defined based on the structural alignment, evolution and structural style as well as Triassic stratigraphic architectures. Transects strike the domain NE-SW. Intra pod rim syncline evolution can be difficult to detail for within the lower Triassic Seismic Unit T1 due to its transparent character. Thickness differences in the domain are clearer in the Upper Triassic Unit T2. Each of the domain is discussed with reference to seismic data.

5.5.1 Area A

5.5.1.1 Lower Triassic Unit T1

Domain A is located in the present day Egersund Basin (figure 5-16). The transect is located in the central parts of halokinetic domain A. In this domain the Triassic Unit T1 display an increase in thickness towards the southeast. The evolution of rim synclines is more prominent in the central part where great local pod differences can be noticed from the cross-section. Wedge shapes are common in the Lower part of the unit especially on the western half graben (fig. 5-16). The depocenters shift from northeast and southwest and are of different magnitude. In the graben to the east, the packages are more parallel but a mega flap sequence is located on the left side of the diapir implying late halokinetic movement. The wedges in the unit show a flip flop trend in the depocenter shift.

5.5.1.2 Upper Triassic Unit T2

The Upper Triassic Unit T2 thickness observed in the transect in figure 5-16 show large variations in the different pods. Although the Unit thickens towards the west, large pod wedging is seen on the western footwall. The most prominent clear depocenters are located on the eastern areas of the pods. Depocenter shift is common in the deposits of the unit but the central pod, where the lower Unit T1 almost reaching the elevation of the salt, the Upper Triassic Unit T2 comprise only gentle depocenter shifts. Abundant Post-Triassic supra salt faulting is dissecting the unit, displacing the Upper Triassic unit T2 rim synclines. The salt walls are generally of the same height, but they become shorter towards the basin margin in the east. The sedimentary are all grounded onto the underlying basement.

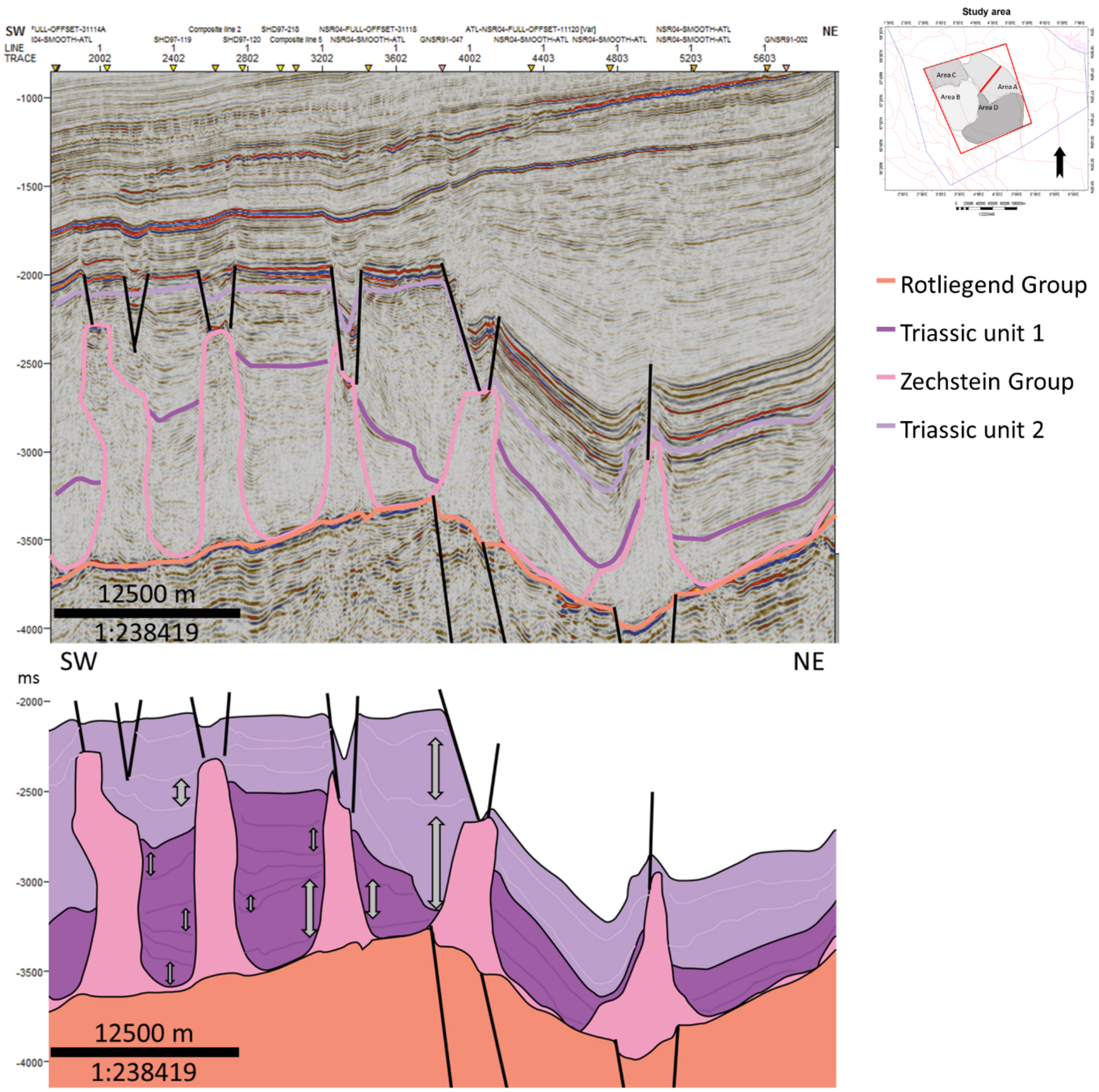


Figure 5-16 Transect of area A located in the central part of the Egersund Basin.

5.5.2 Area B

5.5.2.1 Lower Triassic Unit T1

The Area B cross-section comprises the Norwegian Danish Basin (NDB) and the Sørvestlandet High area. Large thickness variations are seen from the basin on the east side to the high on the Sørvetlandet High. The thickest deposits are located in the Norwegian Danish Basin. The diapirs in the basin (east) are taller features than the walls on the high (west) and the Lower Triassic deposits have almost the same elevation as the salt structures on the high. No vast differences in rim syncline depocenter can be seen on the northeast-southwest transect on figure 5-17. The internal pod rim synclines are tabular to sub tabular for the entire pod succession. On the salt wall seen on the center of the cross-section, the supra salt minibasins with Lower Triassic Unit T1 deposits show signs of eroded synclines where the reflectors terminate by the Triassic Unit T2 base.

5.5.2.2 Upper Triassic Unit T2

The thickness of the unit decreases towards the east. In the basin on the east, the pods have little thickness variations- on the high the unit is very thin and thins towards the west (fig 5-17). The rim synclines are tabular to sub tabular for the entire unit on the transect. The pods in the basin have very equal rim syncline evolution. On the high, the rim syncline hosts minor thickness changes which may be seen on the westernmost salt wall. The salt roller structures located between the salt walls also comprise rim synclines thickening towards the fault center in the hanging wall. On the high, the uppermost strata are terminated due to erosion seen from the truncation of the reflectors. The salt walls in the eastern basin are significantly taller in respect to the structures located in the graben and all the pods have grounded except the pod situated in the hanging wall to the east.

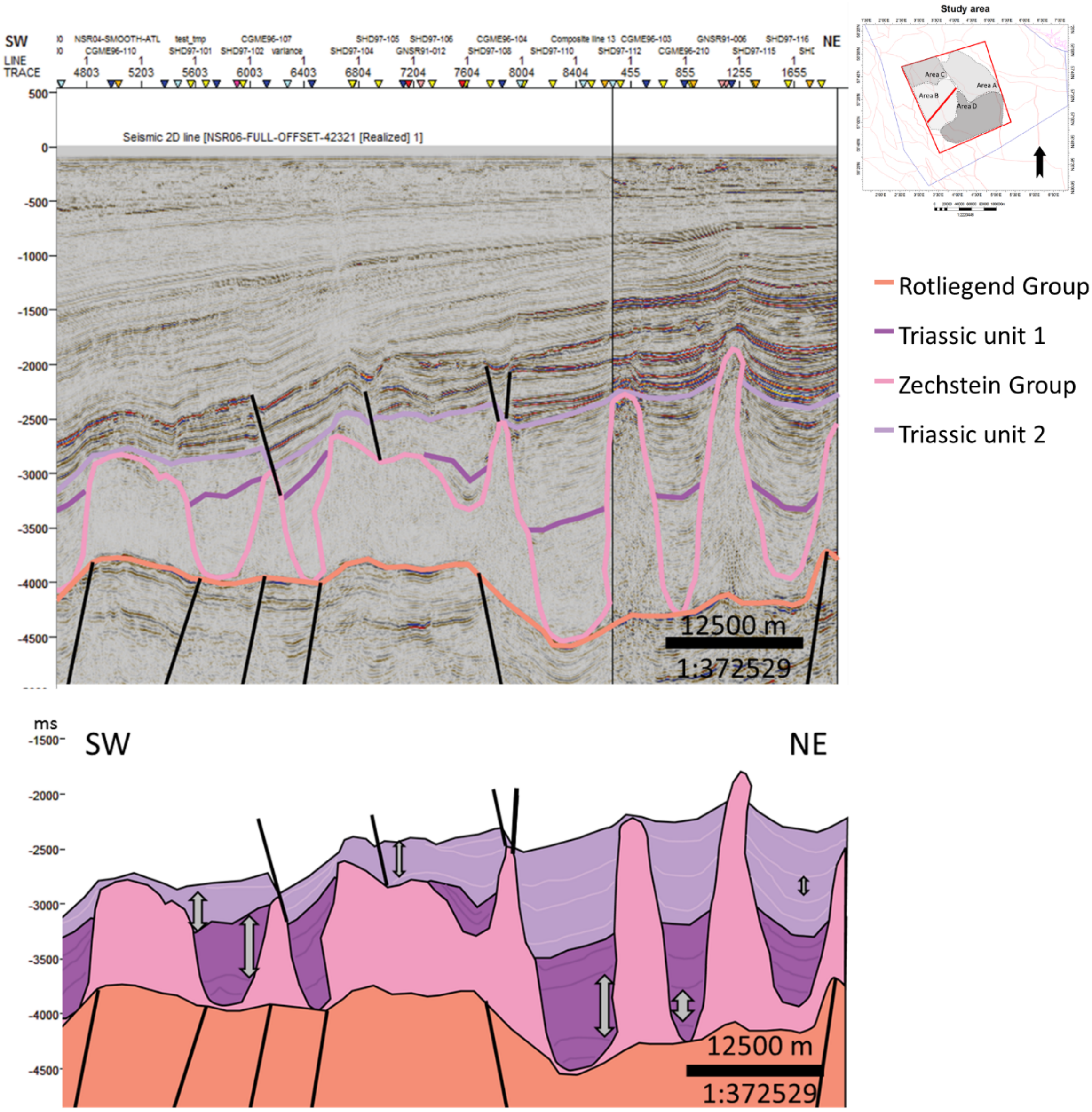


Figure 5-17 Transect through area B. Great thickness differences are seen on the horst (west)

5.5.3 Area C

5.5.3.1 Lower Triassic Unit T1

Area C is located on a structural high in the northwestern section of the study area. The transect of area C comprises the Norwegian Danish Basin and the Jæren High in a NE-SW trend from the Sele High. The unit thickens towards the southwest and holds relatively equal thickness in the three westernmost pods. From the transect in figure 5-18, there is a clear trend that the pods located in the more central parts have greater variations in depocenter in Unit T1. The pods near the Sele high have a more tabular nature. The exception is the one located in the northeast where the deposits thin onto the Sele High and thickens into the tall salt stock. Two turtle structures develop in the unit (fig. 5-18). One is seen in the westernmost pod, whilst the other is on the western side on the horst. The turtle structures generate antiforms and synforms in the pod and are situated on thin layers of salt. The other pods have the shifting depocenter wedge trend.

5.5.3.2 Upper Triassic Unit T2

The thickness of unit T2 is respectively thin in the northeast and with a significant thickness increases towards the southwest. The thickness of the package follows the trend of the surrounding salt. Few great depocenter shifts are located in the seismic cross-section of the unit. The identifiable asymmetrical rim synclines are located in the central pods as indicated in figure 5-18. Otherwise, depocenters mostly thicken by a small magnitude towards the northeast. The salt structures are tallest on the horst in the central part of the transect, except for the tall stock in the northeast. The tall diapir has onlapping strata of Unit T2 and imply post-deposition reactivation.

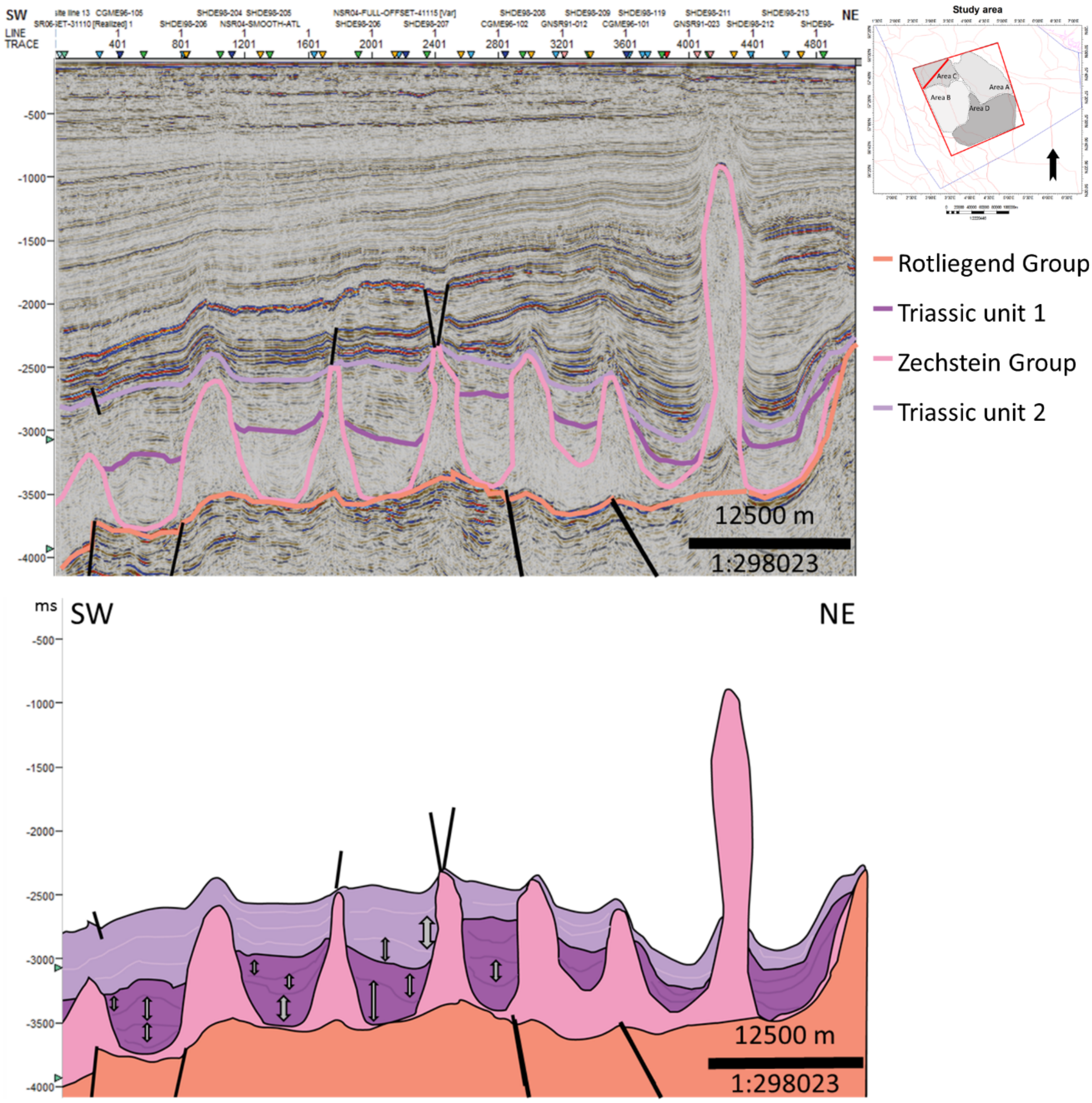


Figure 5-18 Area C cross section. Occurrence of turtle structures in Lower Triassic Unit T1.

5.5.4 Area D

5.5.4.1 Lower Triassic Unit T1

The Area D cross section transect the entire part of the south section of the study area (fig. 5-19) transecting the Norwegian Danish Basin, The Sørvestlandet High and into the Central Graben area. Figure 5-19 illustrate the overall thinning towards the west but with local pod thickness variations. Two thick pods on Unit T1 are located in the southeast. On the other end, the deposits are very thin. Rim synclinal evolution differs within the pods but most of the clearly defined minibasins comprise a trend with thickness increase towards the southwest. Although there are cases where the wedges comprise an eastward thickness increase. The wedges are present on the eastern to the central part of the cross-section. The wedge depocenters vary with great differences in thickness.

5.5.4.2 Upper Triassic Unit T2

Unit T2 thickens towards the east-central part of the area but have a thinning trend from the eastern graben to the west, i.e the deposit thins to the basin margins (fig. 5-19). Gentle asymmetrical rim syncline changes are seen on the eastern pods, towards the east the rim synclines comprise a more tabular expression. The three linked salt walls in the central parts mark the area where the depocenter trends change. On the east side the rim synclines thicken towards the east, whereas on the west side the rim synclines thicken towards the west. The pod comprising the thickest unit T2 deposits have the largest differences in rim syncline wedge geometry. The wedges are thick and are thickening towards the east. The area comprises two tall salt stocks and several salt walls. Truncations in the top of the unit are seen in the west. The pods in the east have grounded but the in the central part and the western part not all pods have grounded but Upper Triassic strata overtop the salt structures.

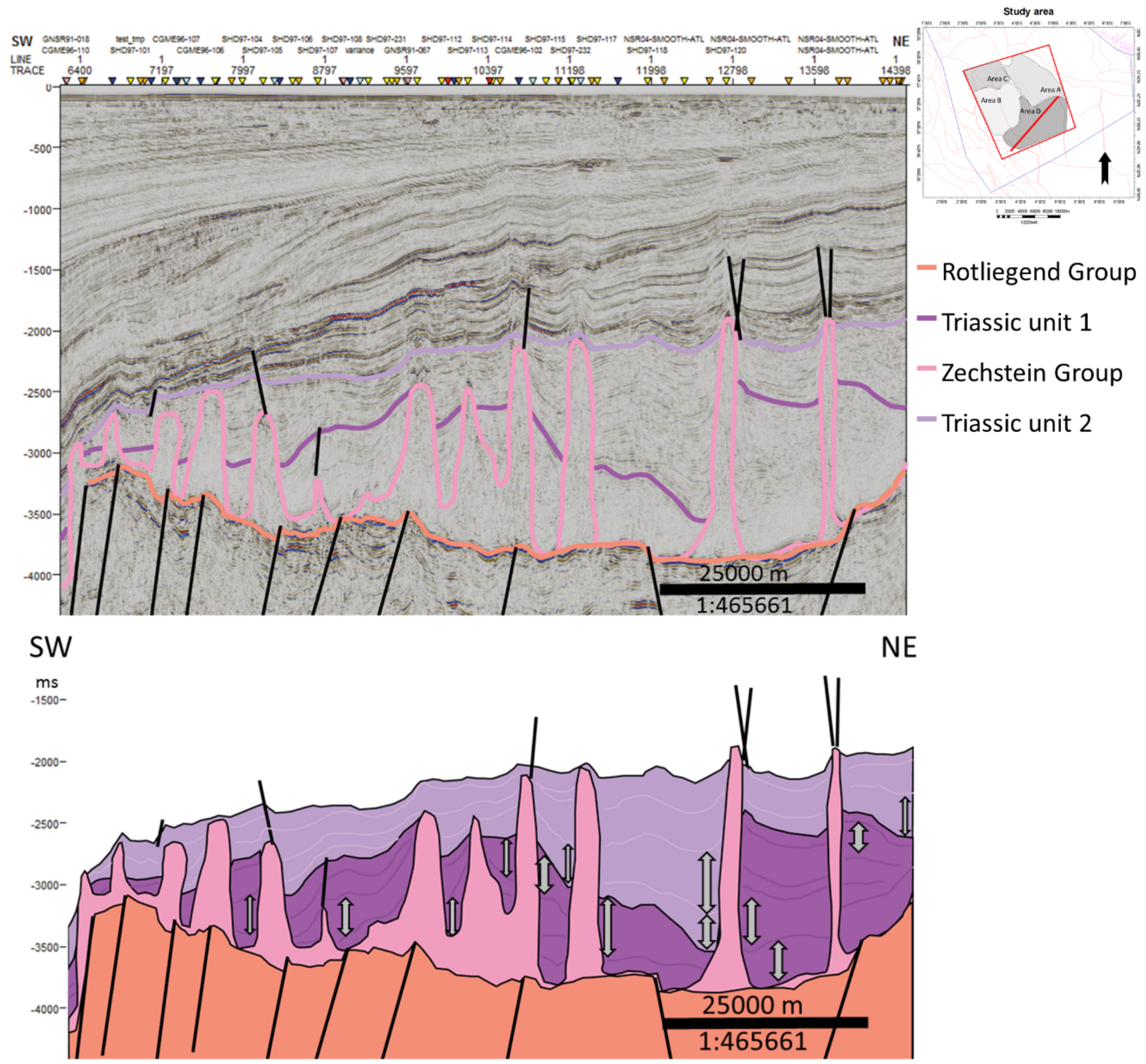


Figure 5-19 Transect through area D going through the lowermost part of the study area and represents a regional transect.

5.5.5 Interpretation

5.5.5.1 Lower Triassic Unit T1

Wedges imply differential loading and are for the Lower Triassic Unit T1 most common in area A and the easternmost part of area D. They imply that the initial fluvial infill most likely was restricted the Egersund basin as the lowermost reflectors elsewhere are more tabular. The thickest deposits of unit T1 are also situated in the same areas (A and D). The wedges may show a flip-flop trend where the depocenter shifts polarity (thickening direction) suggesting that the fluvial stream changed. This may infer that the main influx was in this area during Early Triassic and that floodplain deposits dominated the western part of the area. The extensive, parallel pods show more sign of depocenter shifts than the salt isolated pods located in area B again implying that fluvial streams were not present over the entire area. Looking at a south-north trend transecting trough area D, B and C the deposits of both unit T1 thickens towards the center where the polarity shifts and it starts to thin northwards. The depocenter shifting providing differential loading in the east (area A and D) infer a more rapid halokinetic period of than in the western part of the study area. In the west, the height of the Lower Triassic units and the salt are more alike than in the east where the salt reaches shallower depths than the lower Triassic. The turtle structures from cross-section C (fig 5-18) imply early grounding of sedimentary pods in the northwest, which may be related to initially thin salt layer.

5.5.5.2 Upper Triassic Unit T2

The internal pod wedges are more prone over the entire area than in Unit T1. This suggests that differential loading was not restricted over a local basin and the fluvial streams were distributed more broadly in the area. Although the wedges are more common, they are less extreme in this unit. Superimposed wedges display the geometry and direction, rather than the flip-flop trend of the underlying Unit T1. This may suggest that the halokinetic movement were passive, not active, and mostly defined by differential loading and subsidence due to sediment supply. The wedges often thin upwards as more sediments are deposited suggesting that accommodation space decreases and the eventually overtop the salt structures as seen on the area cross sections (fig. 5-16-and 5-19). The faulting generates a tilt of the pod deposits and may even affect the lower Unit T1, e.g. the western salt roller on transect D (fig 5-19).

5.6 Restored section

5.6.1 Observations

Transect A-A' from northwest to southeast from figure 5-1 was used for a regional reconstruction of the study area. The restored sections display the Triassic basin evolution from the Stavanger Platform to the Central Graben and were restored back in time shown by the steps A- F in figure 5-20.

Line A) represents the original cross section and the present day setting. Removal of the post-Triassic strata from figure 5-20 B, little changes are seen from figure A but the Triassic strata are less compacted and uplifted. Underlying salt is still evacuated into diapirs and not resting on the Rotliegend basement. Figure 5-20 C display that the restored Upper Triassic Unit T2. The line comprises a thick layer of salt on the basement margin. On the central-eastern margin, the salt has been evacuated from underneath the pods. The top of the Upper Triassic Unit T2 is horizontally aligned. Figure 5-20 D removes the Upper Triassic Unit T2 and show an uncompacted Lower Triassic Unit T1 where little changes in salt evacuation are observed from the unfolded Unit T2.

Figure 5-20 E illustrates that the salt layers are thick over the entire basin except for in the east. In the east thinner layers of salt are observed and salt structures are more geometrically defined. The top of the Lower Triassic Unit T1 is horizontal. Figure 5-20 F illustrates the restoration of the subsalt faults. The faults have little to no displacement.

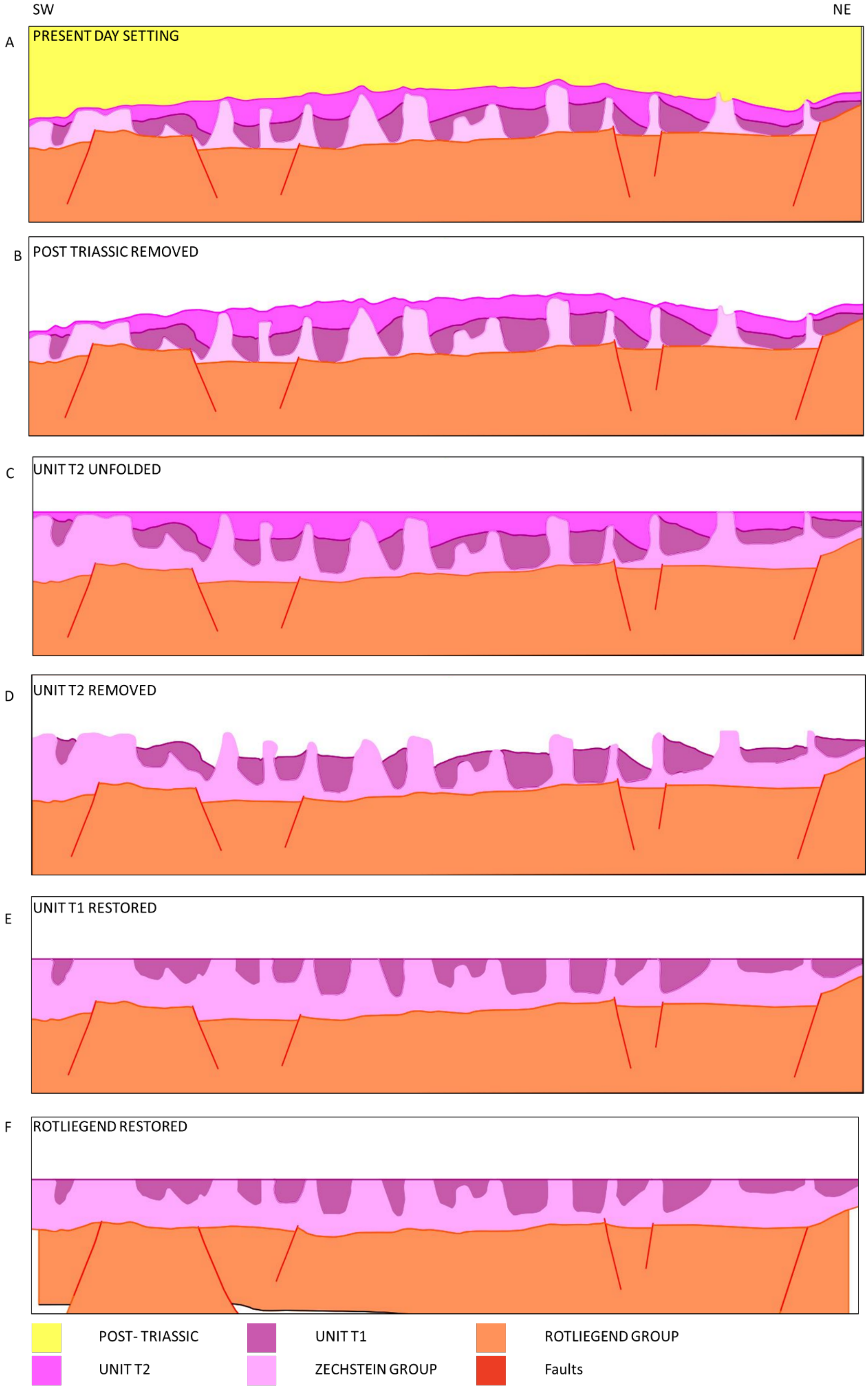


Figure 5-20 The restored sections of transect A-A' from figure 5-1. The restoration steps unfolds the stratigraphic units to the restored Lower Triassic Unit T1.

5.6.2 Interpretation

Figure 5-20 F indicates that the faulting occurred after the deposition of the Rotliegend deposits. This was followed by initial salt structuring. Initial salt structuring was most insightful in the eastern part as indicated by the observation in figure 5-20 E. This suggests that the initial basin structuring was local in the Egersund Basin in response to either local tectonics of sediment infill. Figure 5-20 D indicate that the basin structuring was more regional at the transition to Middle-Late Triassic as it shows the uncompacted Lower Triassic Unit T1.

The restoration to Upper Triassic Unit T2 (fig. 5-20 C) indicates the time of the main basin structuring event. The basin margins were still hosting thick layers of salt but the basin center underwent semi-regional basin structuring. Figure 5-20 B of the post-Triassic removed shows that the basin margin collapse evacuated the salt into structures as a result of regional tectonics. Deposition of the thick post-Triassic strata seen on 5-20 A shows that the Triassic succession has been buried by a thick column of sediments.

The local inital basin structuring indicates that the tectonic pulses may have been locally set in the areas adjacent to the Egersund Basin. As the basin configuration was more regional in the Middle-Later Triassic (figure 5-20 C) it implies that the regional tectonics was an external factor on structuring.

5.7 Interpretation

5.7.1 Basin structuring

5.7.1.1 Late Permian

The Rotliegend deposits show no clear sign of wedging within the data implying that the subsalt Rotliegend Group was subjected to post-deposition thick-skinned faulting. This indicates that the subsalt faults were active during the deposition of the Zechstein Group.

This Zechstein Group is mostly structured into basement fault aligned salt walls, especially seen in the Egersund Basin (fig 5-21 B and C). The salt walls are striking north-south in the same direction as the underlying faults (fig. 5.21 C).

5.7.1.2 Early Triassic (Unit T1)

The tectonic domains display that early Triassic wedging is mostly constricted to halokinetic domain area A and the eastern part of area D (fig 5-21). Early Triassic basin structuring and halokinesis appear to have been restricted to the eastern part in the Egersund Basin as evident from the wedge shapes in the different cross-section (figure 5-1 and 5-21 A) and the restored section. The restored section (fig 5-22 A) indicates that salt exhaustion was greatest in the Egersund Basin as marked by the red square on the cross-section.

The base reflectors in all transects are tabular to sub-tabular to the underlying salt and have an isopachous appearance. This indicates that differential loading in the eastern part occurred after some time of deposition. Alternatively, the localized basin structuring may also be associated with local rifting in the Egersund Basin. The isopachous bedding may indicate that the initial structuring of the salt was dominated by broad salt pillows, which were later restructured into salt walls due to continued rifting and differential loading in the basins.

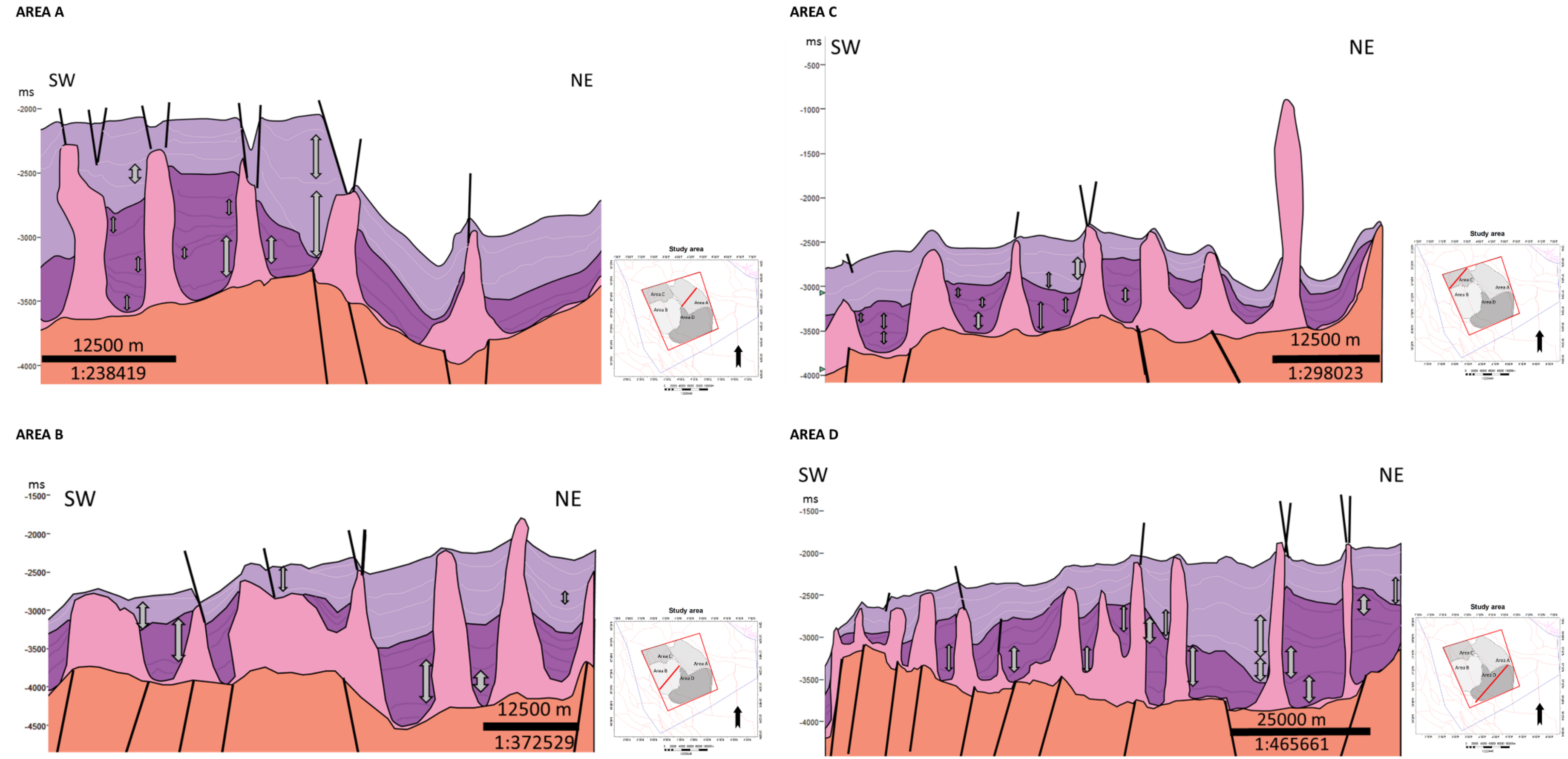


Figure 5-21Changes seen in rim synclinal relationship of halokinetic domain areas A, B, C and D. The transects can also be seen in figure 5-16-5-19.

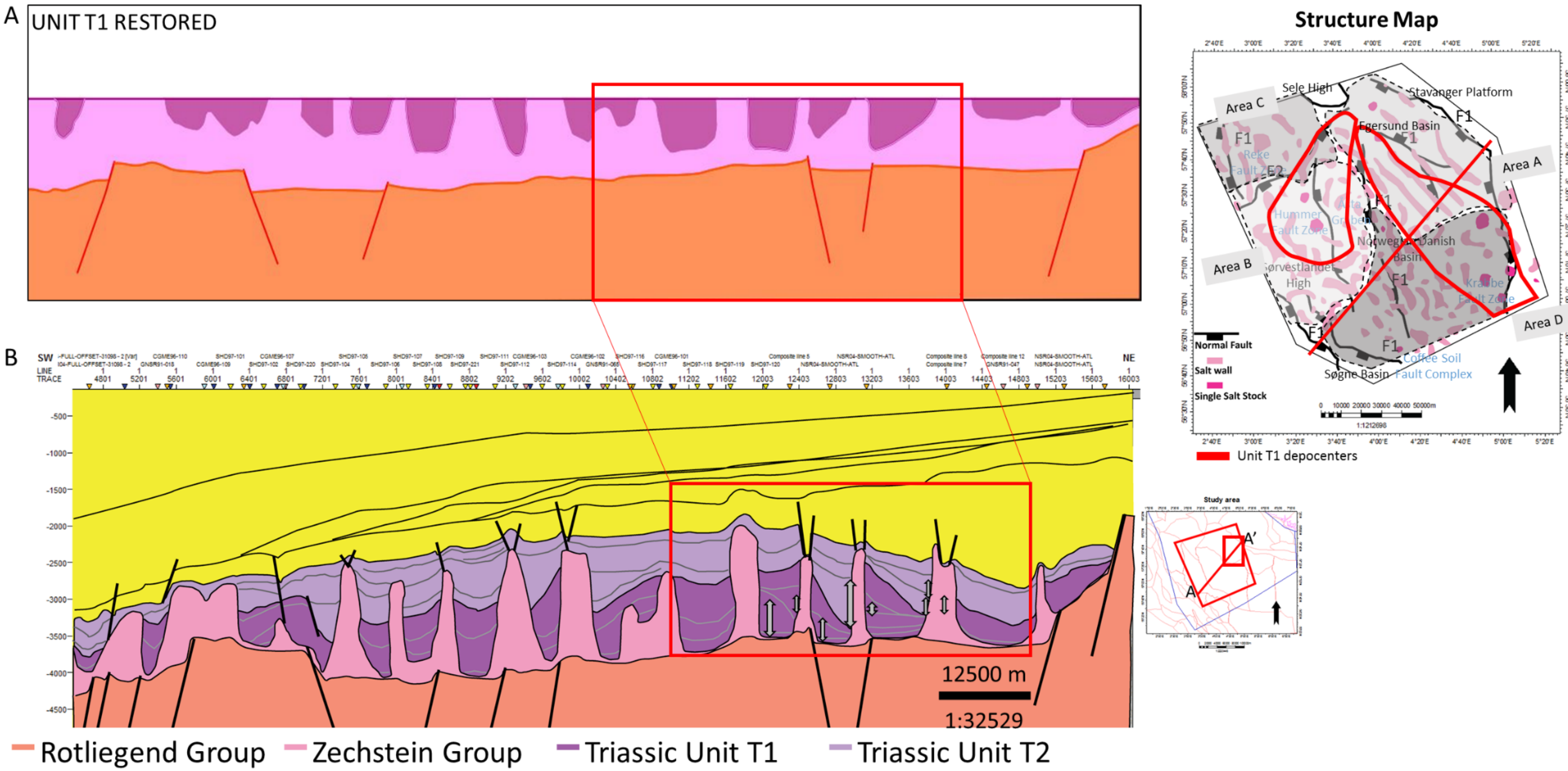


Figure 5-22Basin structuring during Early Triassic. A: The restored profile of transect A-A'. B: The transect A-A' from figure 5-1. C: Location on structure map and correlation to depocenters.The cross sections indicate a localized initial structuring.

5.7.1.3 Middle-Late Triassic (Unit T2)

During the Middle-Late Triassic, the basin experienced a new phase of broad semi-regional generation than in the Early Triassic. The domain transects form figure 5-21 show that wedges within the upper Triassic Unit T2 are more regionally distributed within the unit than in Lower Triassic Unit T1. Figure 5-23 A shows the restored version of Unit T2 which imply that the main episode of basin structuring occurred in the Middle to Late Triassic until the pods grounded and salt was capped by Late Upper Triassic Unit T2 deposits. The increase in basin structuring is also seen from the increase in rim syncline wedges (fig. 5-23 B).

Triassic basin rifting generates the trend of salt structures seen on figure 5-23 B. The rifting controls the alignment of salt creating elongated salt walls. As mentioned the salt structures are aligned to the underlying faults and mainly trend north-south. In domain area A seen on the structure maps this is more clear as salt walls are extensive and parallel. In area B, the western part, the salt wall pattern is more symmetrical; still show signs of a north-south strike. This corresponds to an east-west basin extension.

The bedding trend of the upper Triassic Unit T2 infers that the basins structuring ceases and thickness differences are more isopachous. The earlier stages dominated by reactive halokinesis evolved into a passive halokinetic profile with less differential loading. Basin margin collapse after the Unit T2 Middle-Late Triassic structuring causes the thick accumulation salt. The salt layer was then evacuated into salt walls and stocks as the margins collapse.

Structuring was during this time more pronounced and salt evolved from giant pillows into massive salt walls. This time phase of structuring is time equivalent to rifting phases observed in e.g. the Northern North Sea (Steel, 1993). The extension seems to reflect a basinwide extensional event.

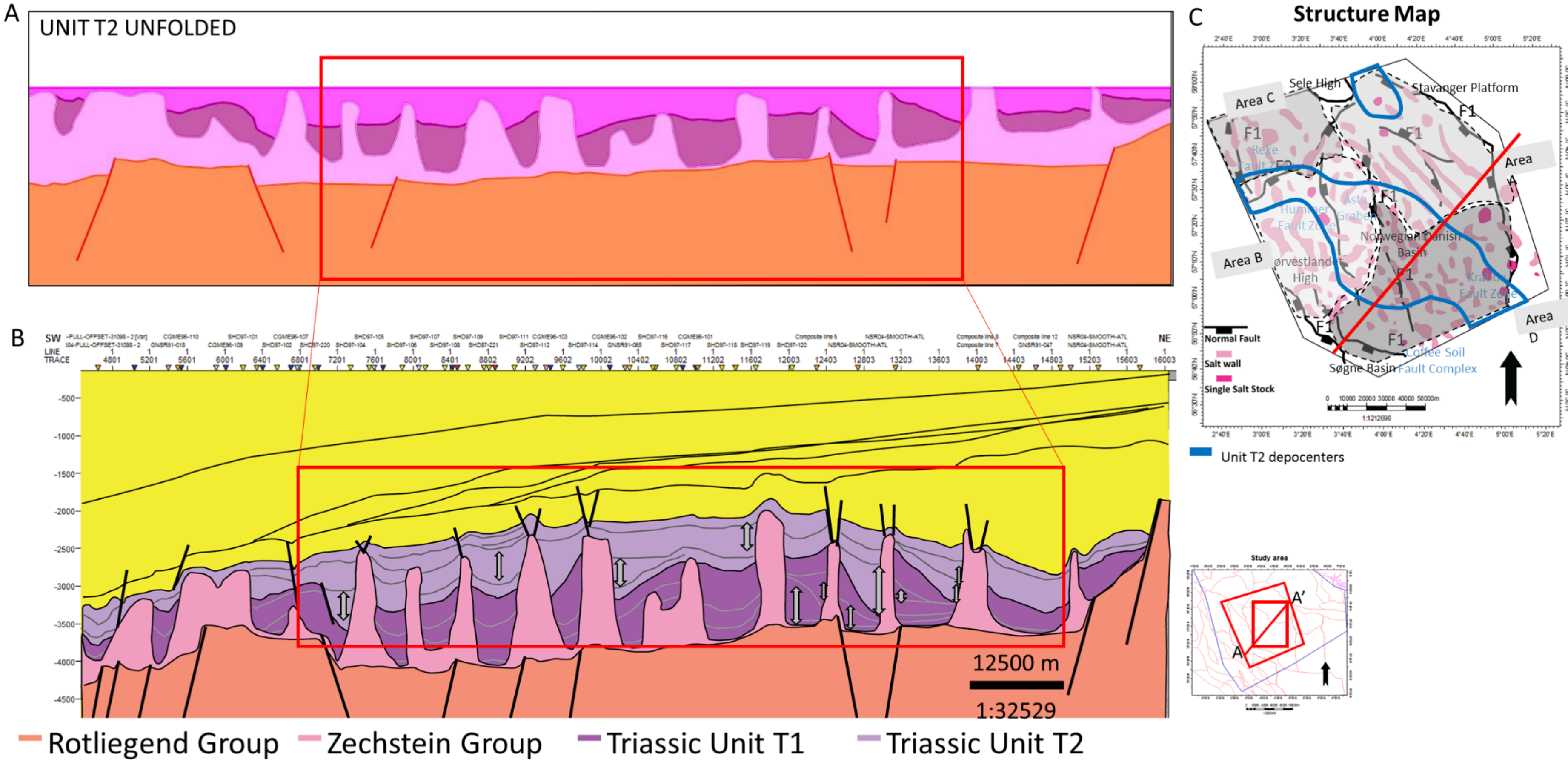


Figure 5-23 Basin structuring during Early Triassic. A: The unfolded profile of transect A-A'. B: The transect A-A' from figure 5-1. C: Location on structure map and correlation to depocenters.Basin structuring are active in the central parts of the basin.

5.7.1.4 Jurassic

Early Jurassic doming resulted in erosion of the Upper Triassic Unit T2 deposits. Supra salt faults are linked to younger activity and correspond to the Late Jurassic to Cretaceous extension and halokinesis. Erosion from the Jurassic uplift is interpreted from stratal terminations in the cross sections in figure 5-21, especially in domain area B and D where the reflectors truncate to the top of Upper Triassic Unit T2. During the Jurassic, the basin margins underwent salt collapse e.g. seen in the Egersund Basin. The Egersund Basin salt withdrawal is seen on figure 5-20 C, B and A where thick salt deposits were exhausted.

Later reactivations are seen from the significantly taller salt stocks which pierce more or less all the overburden as seen on figure 5-2 in the east-west cross-section. Fig 5-2 and the surface map visualizing the top of Unit T2 (fig. 5-7) shows that smaller diapirs also pierces the Triassic strata, these are more common in the east rather than west where they pierce significantly into the overburden.

5.7.2 Structural Style

5.7.2.1 Late Permian

Late Permian basin configuration and orientation are illustrated in the structural map in figure 5-24. The structure map indicates a graben system evolved during deposition of the Zechstein Group shortly after the deposition of the Rotliegend Group. The Rotliegend fault complexes are normal faults dipping to the east and west corresponding to the E-W extension (fig 5-1 and 5-2 illustrate fault dip direction).

The Late Permian basin configuration was one of the extension episodes during Mesozoic. The extension created a broad full graben and asymmetrical half-grabens that were infilled with evaporates from the Zechstein Sea. Salt structures allow for the identification of halokinetic domains (section 5.5). The salt structures appear to have been controlled by the Permo-Triassic extension initially and later supported by differential loading.

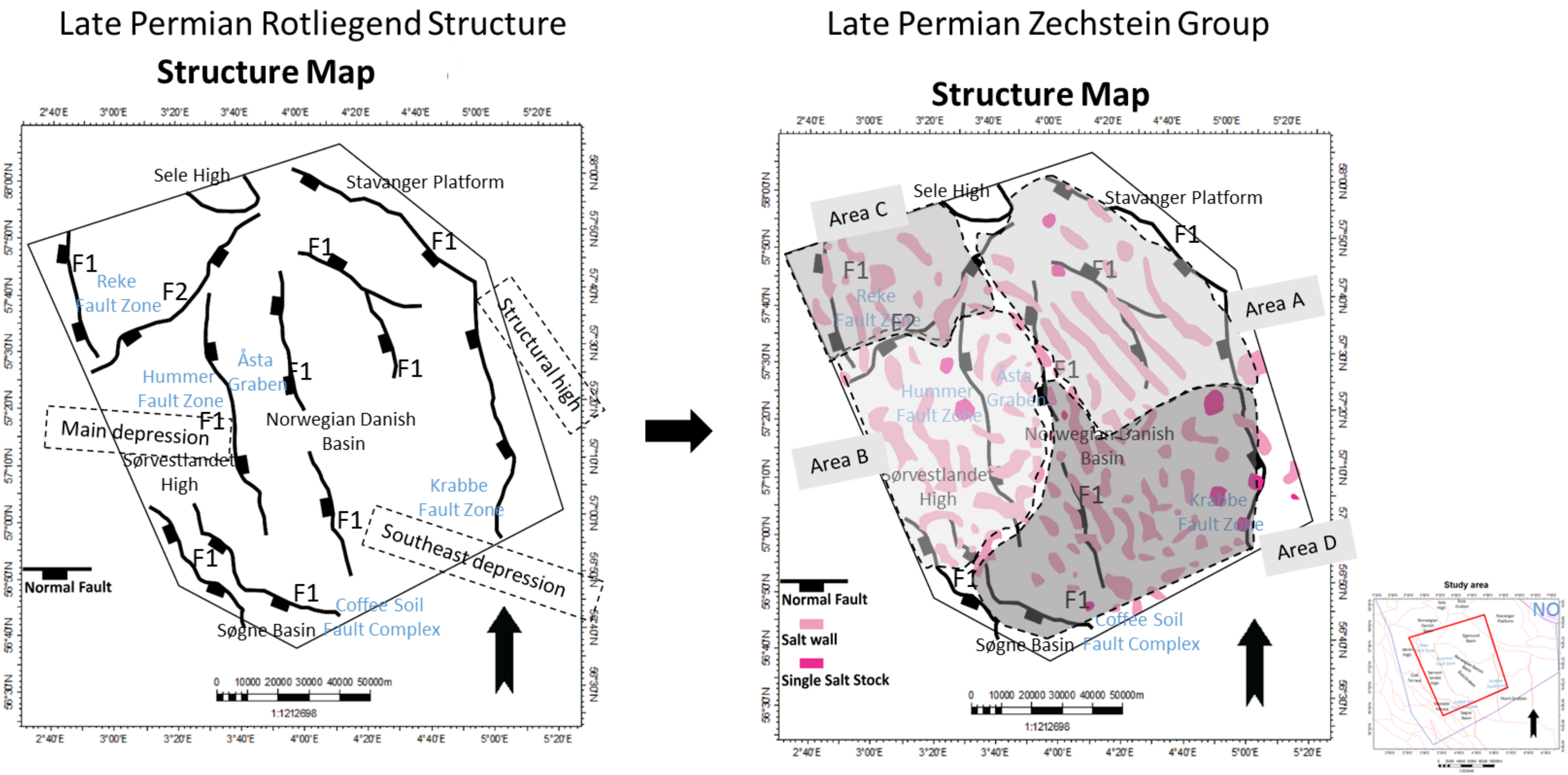


Figure 5-24 Structure maps showing the Late Permian tectonic evolution. The Rotliegend map (left) shows a network of fault complexes. The Zechstein structure map shows the interplay between sub salt fault complexes and salt geometries.

5.7.2.2 Salt Structures

The tabular nature at the base of Lower Triassic Unit T1 (Unit T1) implies that deposition was uniform and comprised broad sheetlike strata (fig. 5-21, 5-22 and 5-23). This suggests that the initial salt structure was broad pillows that had gentle relief. They formed at the early onset of basin extension and sediment loading in the Egersund Basin, halokinetic domain area A. As discussed in section 5.7.1.2 this area of early halokinesis coincide with Lower Triassic Unit T1 depocenters and thus differential loading may actively have contributed to the triggering of salt remobilization. Differential loading is further suggested by the flipping of stratal wedges in turn related to lateral shifting or avulsion of the fluvial dispersal system. Differential loading and extension generated the present day evolution and alignment of salt structures seen on figure 5-24.

The chart in figure 5-25 by McGuinness and Hossack (1993) shows the geometric shape of salt structures based on the interplay of sediment supply and salt supply. The diapirs from the study area plots within the lower section of the diagram. The lines representing the relationship of 60 degrees are the common trends in the study area and imply that sediment supply rate were at some degree higher than the underlying salt evacuation.

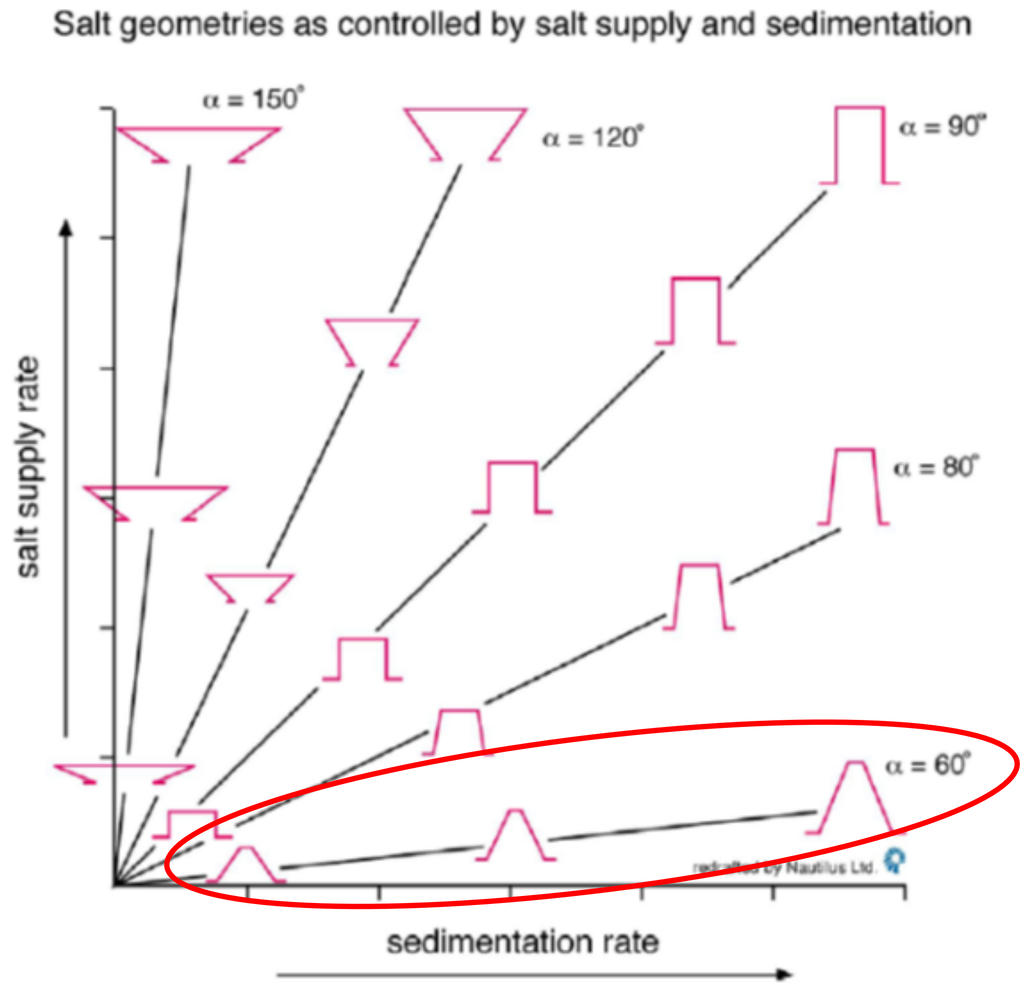


Figure 5-25 Relationship between sedimentation rate and salt growth, the res oval represents the salt structures in the study area (McGuinness & Hossack, 1993; Moraleda, 2015).

Salt walls are the dominant structural salt style and are commonly encountered in all halokinetic domains. Salt stocks are less common but a few tall salt stocks are present on the Sørvestlandet High in halokinetic domain B. The restoration (fig. 5-20 C and B, 5-22 and 5-23) indicate that halokinetic movement paused in Middle-Upper Triassic and ceased to influence pod structuring.

5.7.3 Basin Infill Trends

5.7.3.1 Early Triassic

The transparent seismic character and the inform mud prone lithology imply a depositional environment dominated by floodplains or terminal playas, sabkhas or lacustrine systems.
The restored section and the location of wedges seen in domain area A indicate that the main basin infill in Early Triassic was in the Egersund Basin and Åsta Graben. The restored section and the depocenters in the Unit T1 isochore imply that the main sediment influx was restricted to domain area A. Figure 5-26 shows the structure map and depocenters and the suggested sedimentary influx in the north-northeast.

The basal Triassic tabular reflectors from the cross-sections (fig. 5-21) indicate floodplain strata in the lower Lower Triassic Unit T1. On the other hand in the northeast, the wedges shift locally in the pods at an early stage, halokinetic domain area A (fig. 5-21). The wedges imply a different clastic sand input related to sheet floods, perennial rivers in fluvial fairways suggested by the lithological interpretation. In figure 5-14, channel facies positioned in the upper part of seismic unit T1 are laterally elongated features. The channel facies imply a fluvial system with very shallow, sheet-like streams corresponding to less discontinuous streams of ephemeral style in an arid desert-like depositional system.

The isochore map in figure 5-6 from section 5.1 infer that deposition took place in local salt related basins. The local depocenter imply that sediment supply was greater than the accommodation space. This suggest an infill and subsequent spill and at the time the fluvial system may have prograded away from the Egersund Basin (see ch. 6). The sediment supply caused by ephemeral fluvial streams resulted in differential loading on the salt and subsided as salt was evacuated into rising salt walls.

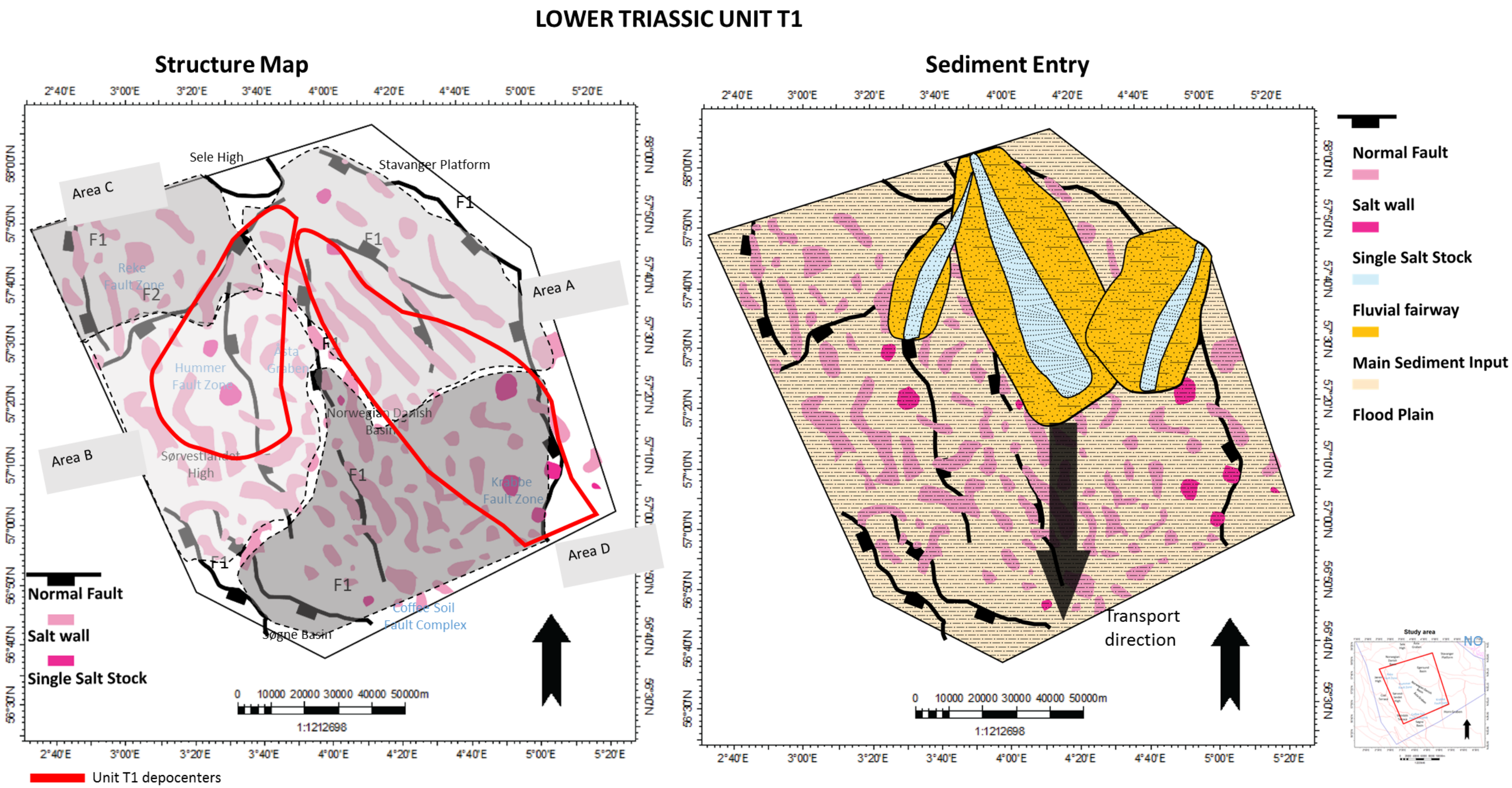


Figure 5-26 Suggestions to sedimentary influx during Early Triassic. The left map illustrates the location of the depocenters. Right: figure showing the main entry point in Early Triassic.

5.7.3.2 Middle Triassic

A backstepping of the fluvial system occurred as a result of either tectonic rifting or change in climate occurred during Middle Triassic. The backstepping generated a widespread floodplain dominated by shale deposition in the Norwegian Danish Basin. The basin was potentially flooded by marine waters along the Egersund Basin. At the time of shale deposition, accommodation space creation was higher than sediment supply. The deposition of shale may be related to a lacustrine intrusion related to or just a change in the climate.

5.7.3.3 Late Triassic

In the Late Triassic the sandy basin infill was covering larger areas of the Central North Sea. The cross sections imply that differential loading was widely distributed during Middle-Late Triassic (fig 5-21). In the Norwegian Danish Basin, a stratigraphic evolution is inferred from four main stratigraphical evolutions. During deposition of unit T2, the channel systems develop through time. It starts to develop as a multistorey isolated channel belt to semi-lateral and multistorey channel fills filling the sub-basins. Ultimately the channel belts are laterally extending over the salt walls (figure 5-14).

Early on rim synclines indicate that the accommodation space was larger than sediment supply. Steady streams indicate creating multistorey connected channel belts as seen from figure 5-13. Broader asymmetric basins dominated during deposition of the Middle-Late Upper Triassic Unit T2. These rim synclines are shown in figure 5-14 as broad rim synclines hold the same lateral extent as the sub-basins. The accommodation space creation was larger than the sediment supply. Following the last evolution of asymmetric basin infill into rim synclines, the sediment supply and accommodation space were more or less equal. At this stage, the sediment supply filled the basins to its maximum infilling the topographic lows.

Diapir overtopping occurred at the latest stage of the Late Triassic basin infill history. The sediment supply was at this stage larger than the accommodation space and the sub-basin subsidence ceased due to the pause in salt structuring. The fluvial systems most likely prograded beyond the Norwegian Danish Basin.

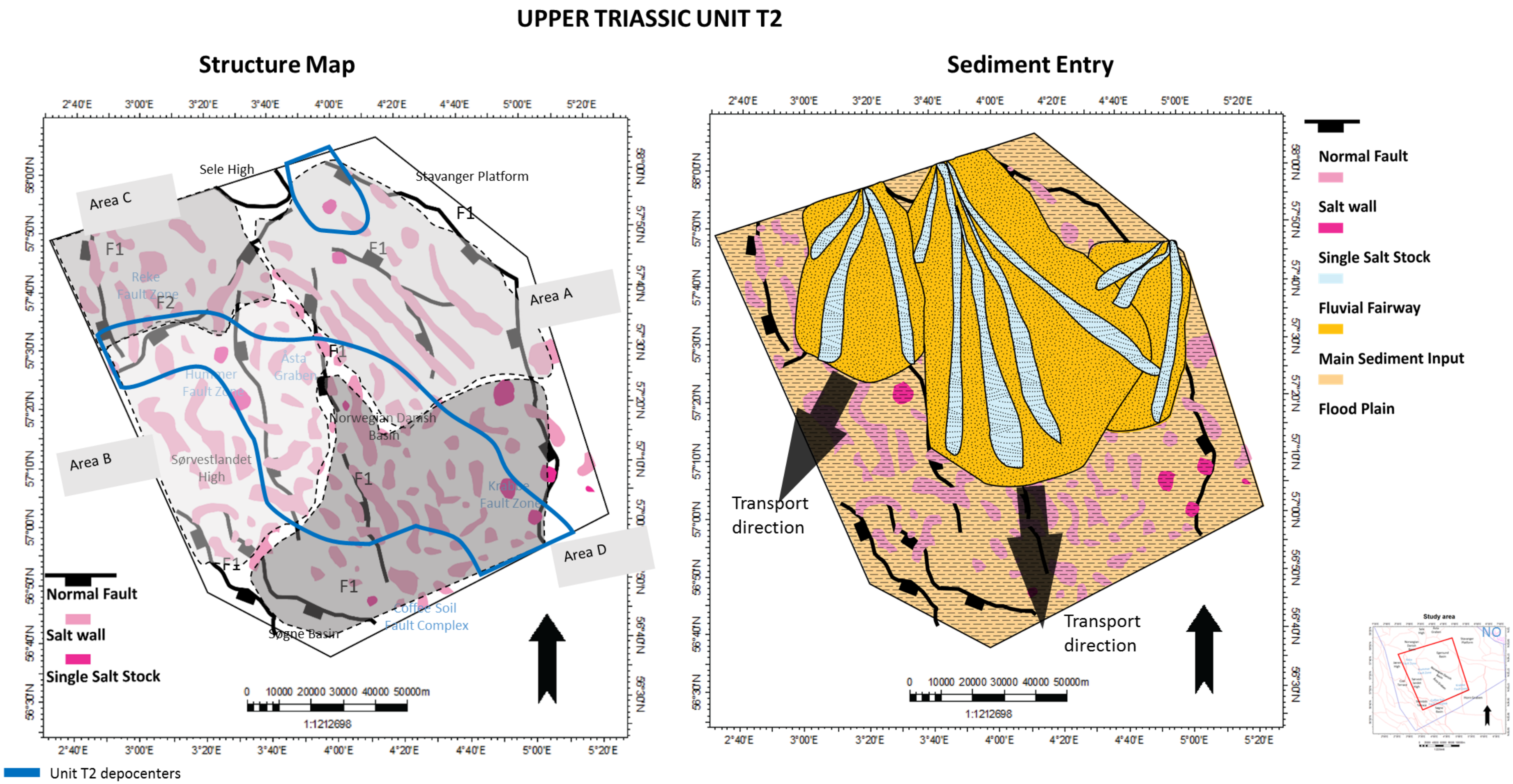


Figure 5-27 Suggestion to sedimentary influx during Middle-Late Triassic. The left map illustrates the location of the depocenters. Right: figure showing the main entry point in Middle to Upper Triassic.

6 DISCUSSION

6.1 Integrated Triassic Tectonostratigraphy

6.1.1 Early to Middle Triassic Basin Evolution

Late Permian extension by thick-skinned normal faulting produced an array of grabens and half-grabens (figure 6-1). The deep grabens was filled by Late Permian Zechstein evaporates and later on, it was filled by Triassic continental deposits. Early Triassic deposition in combination with extension eventually triggered salt remobilization as active diapirism. Early active diapirism was likely enhanced by sediment loading from active fluvial synforms were present in the initial stage of halokinetic structuring. The depocenters deposited during the early stage of salt withdrawal basin were parallel to the early salt pillows/walls. The depocenters late evolved into wedges as demonstrated in figure 6-2.

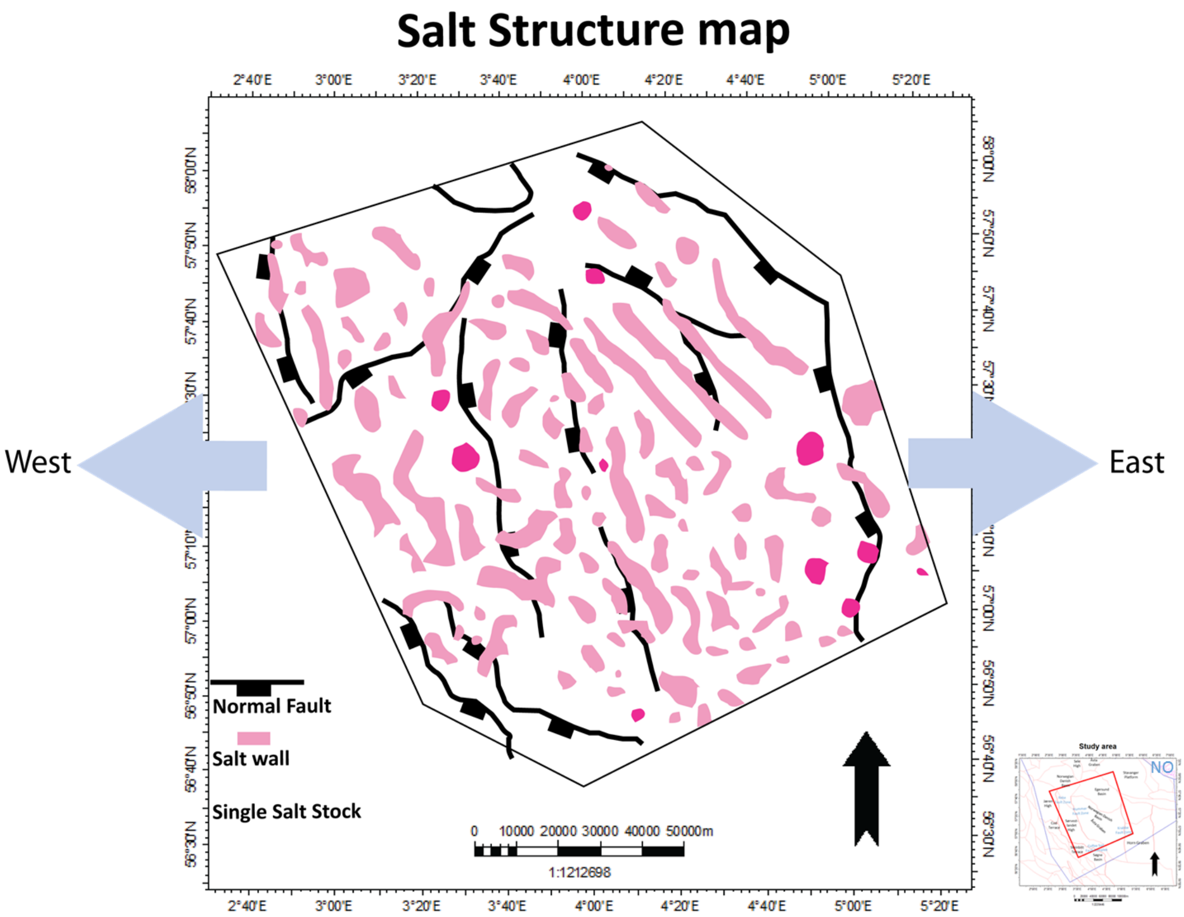


Figure 6-1 Map illustrating the Permo Triassic extension orientation marked by the arrows. Both the normal faults and salt structures are representative of the present day setting.

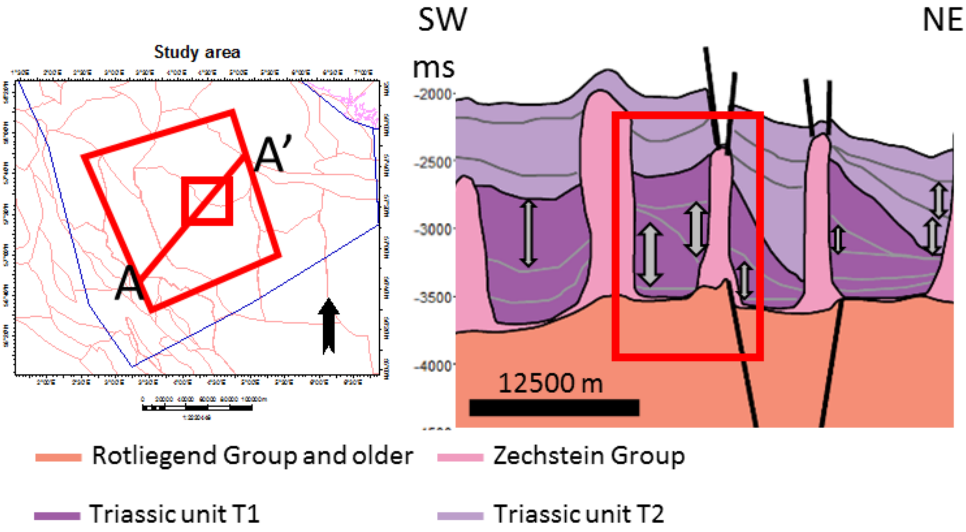


Figure 6-2 Detailed section of the transect in figure 5-1 showing the flipping of depocenters locally occurring in the pods in the Egersund Basin.

McKie (2017) suggest that the Anisian fluvial palaeo current was derived from the Norwegian and UK hinterland transported across the Åsta Graben (fig 6-3A). The fluvial infill trend coincides with the northern orientation of the salt walls filling the sub-basis parallel to the salt walls The fluvial streams filled the sub-basins axially in relation to the extensive salt structures demonstrated by figure 6-3 B. The fluvial sediment influx demonstrated on figure 5-26 coincide with the northern orientation of the salt walls filling the minibasins parallel to the salt wall (Banham & Mountney, 2013). As discussed differential loading might have been a dominant driving mechanism of the initial halokinesis. The differential loading in an axial delivery indicate that the salt walls grew at different rates suggested by salt evacuation and seen on the restored section in figure 5-21 and 5-20 F and D. This can be seen from the flipping of asymmetric synclines in figure 6-2, where the wedges thickens to the salt at different times of deposition.

The basins were filled with proximal to distal fining of fluvial to muddy floodplains with progradation as the sub-basins fill to spill. As illustrated in figure 6-3 b) some basins are more sand prone and some are muddier. The sandier basins are located in the northeastern central parts of the study area, this is related to the position of the fluvial sheet floods. The shifting of depocenters indicates that the floods follow the lowest topography. The retreat of the fluvial system in Middle Triassic basin structuring enhanced subsidence rates and resulted in local marine transgression or lakes or playas.

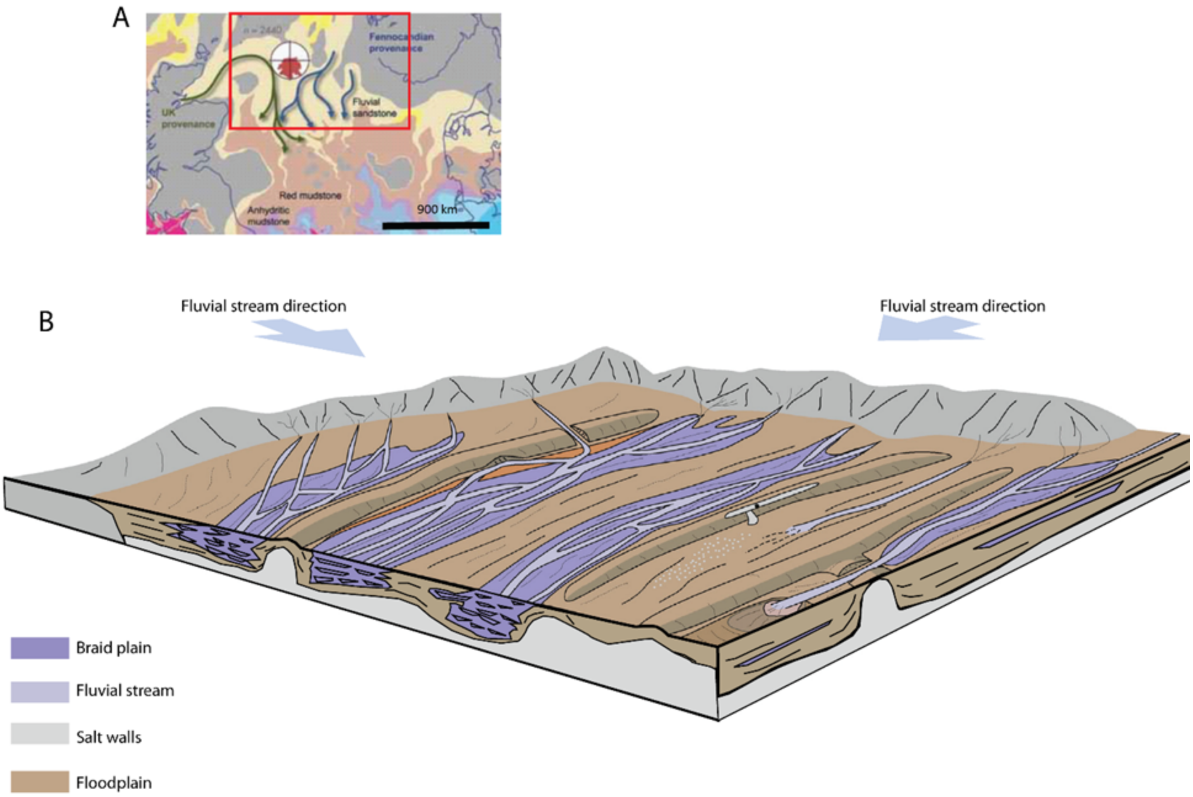


Figure 6-3 The fluvial infill trend during the late Anisian (Middle Triassic). B: conceptualized model of double sediment infill. Modified from McKie (2017) and Banham and Mountney (2013). The figures illustrate that the sediment delivery was axial along the salt walls.

The palaeographic maps of Mckie and Williams (2009) indicate a shift in depositional style from general fluvial sand dominated deposition in Early Triassic, Olenekian to deposition of playa muds in Middle Triassic Anisian. The environmental changes are seen from shale deposition interpreted in chapter 5.3. The strong amplitude seismic marker is most abundant within area B defined by isolated minibasins. The isolated minibasins are prone to the development of ephemeral lakes, which can result in intra basinal lacustrine flooding corresponding with the GR log response seen on figure 5-9. The ephemeral lakes deposit fine-grained sediments and can be an abrupt change from the surrounding coarser sedimentation. Figure 6-4 shows a conceptualized figure of the deposition of Early Triassic in the Central Graben, the basins are underfilled with isolated belts and demonstrate an ephemeral lake (Banham & Mountney, 2013; Hodgson et al., 1992).

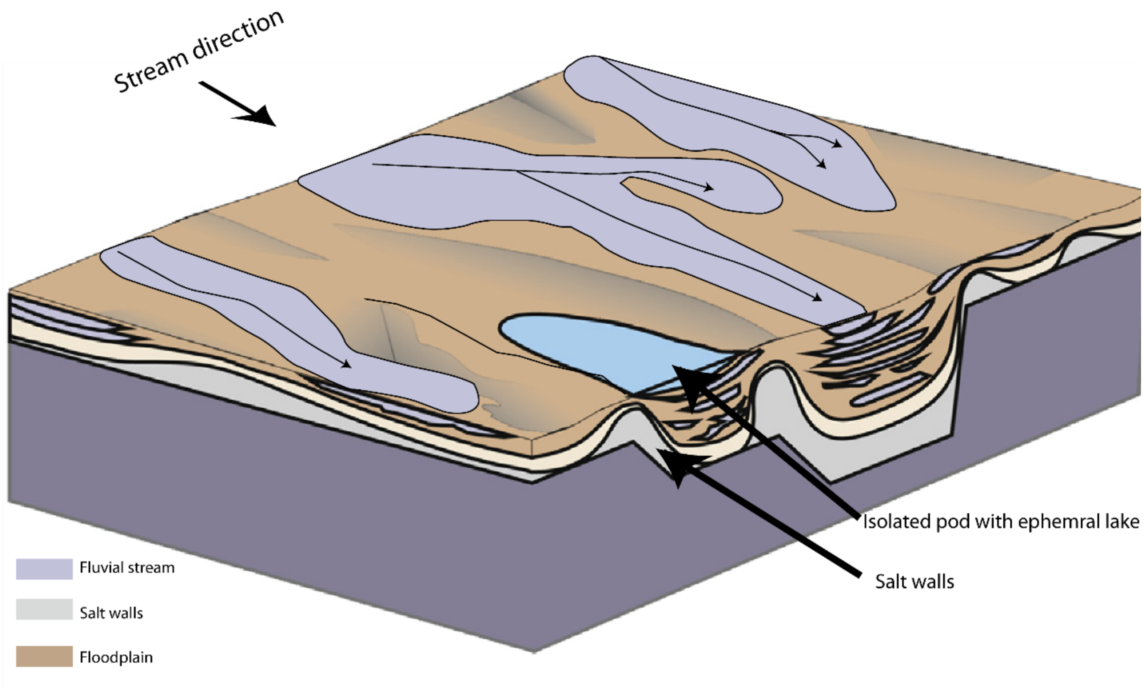


Figure 6-4 Conceptualised model of the Early Triassic infill in the Central Graben modified from (Banham & Mountney, 2013; Hodgson et al., 1992)

6.1.2 Middle to Late Triassic Basin Evolution

Renewed basin structuring in the Middle Triassic triggered a new stage of basinwide salt remobilization. Initial broad subsidence at increased rates caused the fluvial systems to retreat and accommodation space was higher than sediment supply resulted in passive diapirism. Then salt movement again increased and pods started to ground. The sub-parallel bedding implies that the salt diapir rise was more prone to the passive down building deposition as the flip flop patterns are prone to salt rollers and active faulting (Quirk & Pilcher, 2012).

There is also sparse evidence of middle to Late Triassic tectonics as little Triassic faulting is barren within the seismic data. The evolution coincides with the Triassic evolutionary model proposed by Aarseth (2019) in his thesis work. The evolution model was based on reactivated diapirs from the Ula area. The reconstructed section (fig. 5-20) infer that basin structuring evolved from being restricted to the Egersund Basin in the northeast now were active in the entire central basin. Grounding of sedimentary pods occurred initially in the central parts of the Norwegian Danish Basin and then the basin flanks (Sørvestlandet High/ Central Graben and Egersund Basin) salt grounded.

The fluvial systems were more stable during the Middle to Late Triassic and were separated by periods of less fluvial activity. Figure 6-5 display three levels of channel deposition in Upper Triassic Unit T2 (sequence 2, 3 and 4). The lower channel evolution of sequence 2 accumulates asymmetrically in rim synclines. The channel belts are stacks of shallow semi- multilateral and multistorey fills. The middle channels are broader and extend areally over the entire minibasins but are restricted by salt walls. The subsidence is more equal and the differential loading is not as severe as in the lower unit. The channel fills from sequence 3 are multistorey and multilateral channel belts with good connectivity both laterally and vertically. The upper channel belt deposits cover the entire basins overtopping the salt walls. the channel belts are laterally extensive and expand over the salt walls. The upper channel belts of sequence four marks the end of main Triassic basin structuring inferring that basin subsidence ceased prior to deposition. Later halokinetic movement was induced by later tectonic pulses.

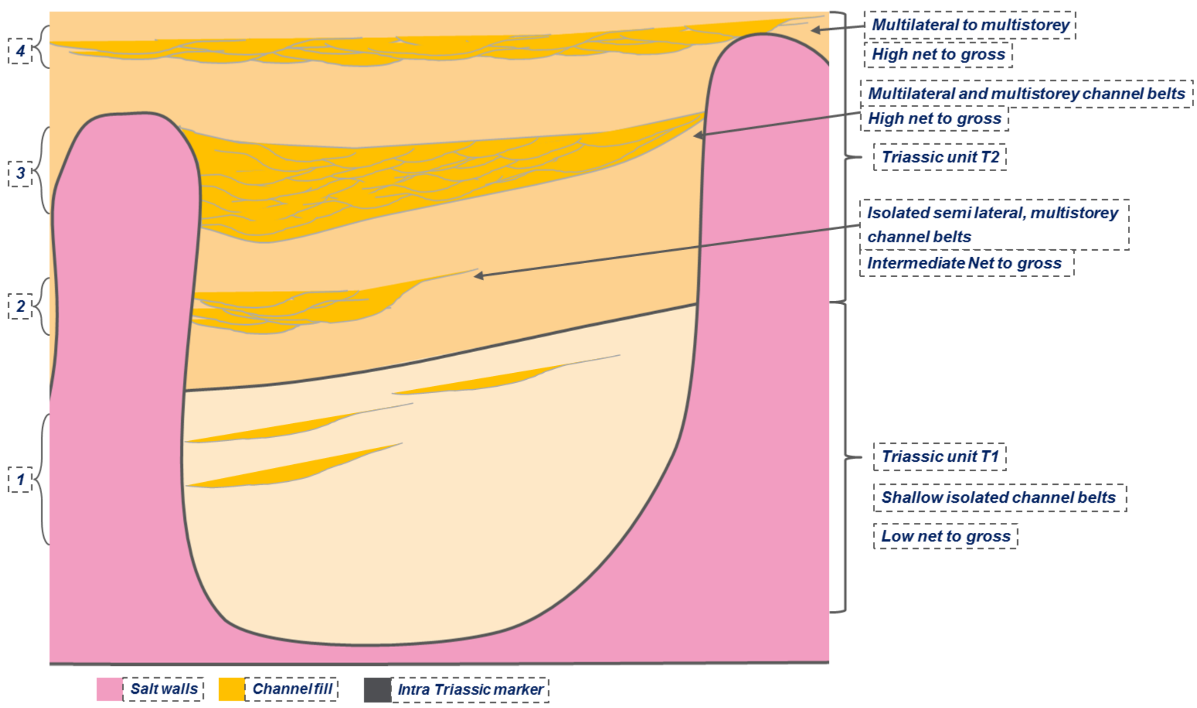


Figure 6-5 Conceptual model of the fluvial stacking pattern sequences of the Triassic in the central North Sea. Based on the channel belt evolution described in figure 5-13.

The interpreted fluvial influx was wider than in the Early Triassic. Figure 5-27 explains the main sediment entry point in the Norwegian Danish basin. The depocenters interpreted from the Upper Triassic Unit T2 isochore (fig. 5-7) indicate that the sediment influx was sourced from both northern and eastern areas and that the. The depocenter trend may suggest sediment influx from the northeast during Middle-Late Triassic mixed with a northern influx defined by the northern minor depocenter. Similar entry points were interpreted by Gulyaeva (2016) in the Norwegian Danish Basin. Mckie and Williams (2009) and other authors work on the central North Sea Triassic deposition suggest drainage from the Scottish Highlands and the Fennoscandia Shield, which match the inferred entry points in this discussion. The provenance is based on geochemical data of the Skagerrak Formation and proposes dominant drainage oscillating from the Scottish Highlands and the Fennoscandia Shield. Herein the sediment source is interpreted to represent proximal fluvial fans derived from the Norwegian Hinterlands representing axial transport to the subbasin

The fluvial delivery to the pods during Middle to Late Triassic was still axially aligned to the salt walls in halokinetic domain area A where the walls are oriented parallelly. In area B dominated by isolated pods and asymmetrically distributed salt walls the infill were delivered towards the-southeast filling the pods axially and transverse. The axial and transverse fill can also be interpreted to occur in area C and D were the salt walls are randomly distributed. The fluvial channels mapped in figure 5-13 and conceptualized in fig. 6-5 transects the study area in an east-west cross section and may imply that some rivers had a northeast/east orientation in the central to western sections of the study area (domain area B, C and D). The maps from Jarsve et al. (2014) indicate a north and northwestern stream influx (blue arrows figure 6-6).

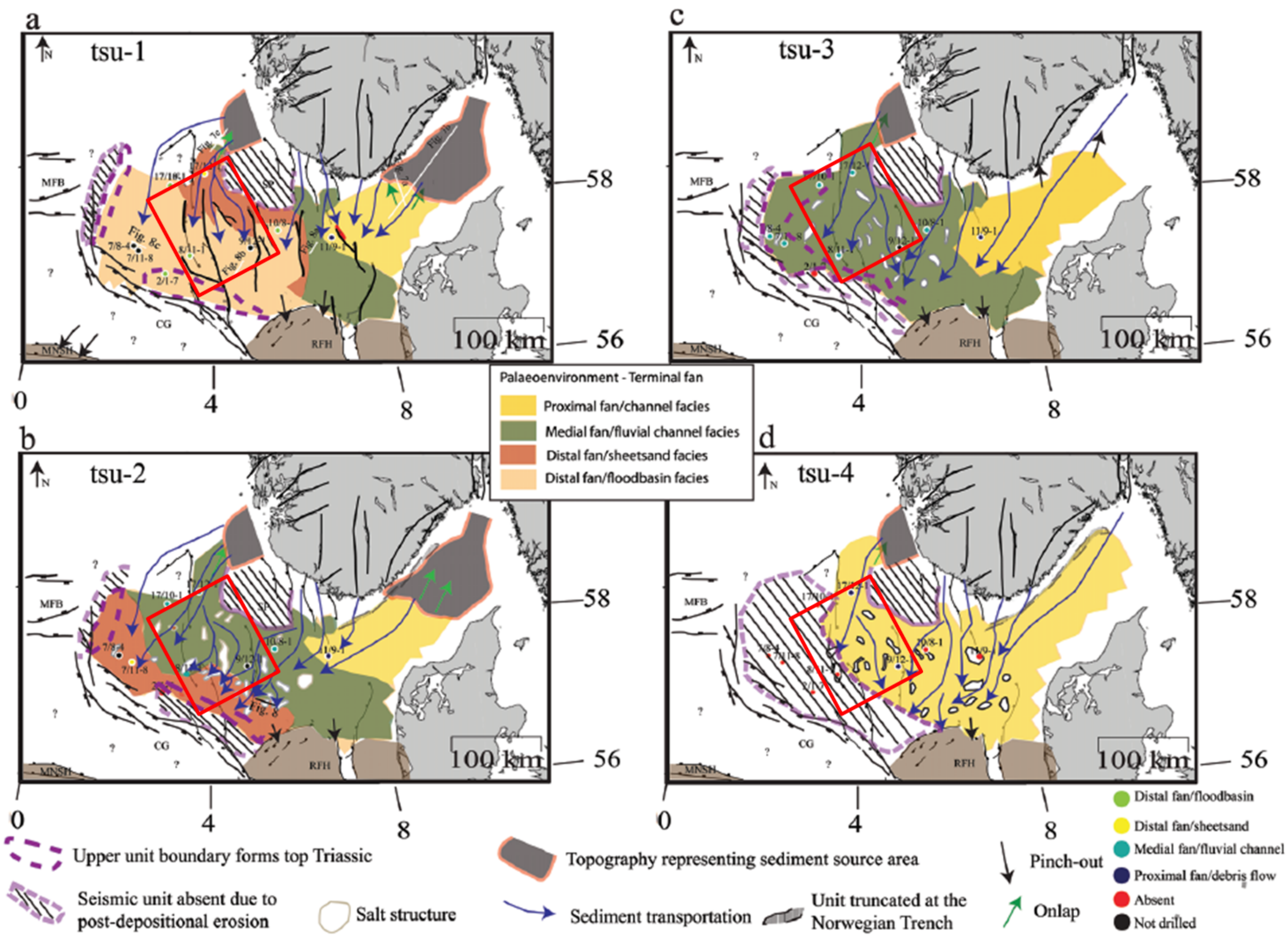


Figure 6-6 The depositional transition in the Southern and Central North Sea during Triassic, the study area is marked by the red square. Tsu-1 correspond to seismic unit T1, whilst seismic unit T2 includes the remaining three units. (Jarsve et al., 2014)

6.2 Triassic Play in Norwegian Danish Basin

6.2.1 Trap Types

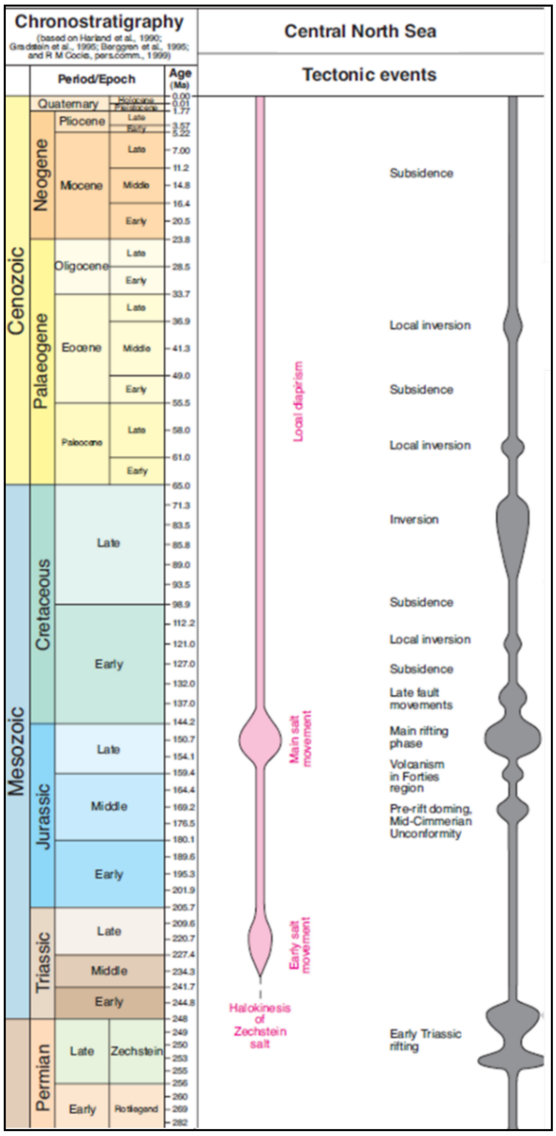


Figure 6-7 Halokinetic evolution in the Central North Sea. Modified from (Zanella & Coward, 2003). The chart indicates the salt evolution and trap modification in the Triassic reservoirs.

The single most abundant structural trap style within the Triassic unit T1 and T2 are structural traps generated by salt walls and diapirs (fig 6-9). Salt generates structural traps located on the flanks and they may cause supra salt deformation as anticlinal features. The initiation of the salt structures in the Norwegian Danish Basin (NDB) commenced in the Early Triassic simultaneously with the Permo- Triassic extension and deposition of unit T1. This can have combined structural and stratigraphic traps along the flank due to fluvial reservoir pinch out onto growing structures. On the other hand, the main salt movement occurred in the Late Jurassic Early Cretaceous series along with a second extension phase and minor local inversions happened in Cenozoic (Zanella & Coward, 2003). The salt movement is summarized in figure 6-8 and the different phases generated the present day structural evolution of the salt structures in the area. Not all structures reactivated during the main halokinetic pulse as cross sections in figure 5-1 and 5-2 indicates that Triassic burial of salt structures is a common feature in the study area. This is especially seen on the transect through area A, whereas single features pierce the Triassic succession on the transects of area B, C and D. The burial of the diapirs restricting the deformation of the Triassic reservoirs preserving the initial reservoirs. Post Triassic reactivation may potentially risk the seal preservation, whereas the salt structures that have not been reactivated are more likely to have an intact trap.

Stratal traps may be proposed in rim synclines where fluvial reservoirs were deposited. Later basin tilting created migration pathways and traps. Transect D, fig 5-23, illustrates a salt roller, which generates both a fault displacement trap and potential salt flank traps. Early grounding of sedimentary pods generates sedimentary highs in the study area. A Turtle structure is evident in area C in the westernmost pod. Supra salt faults can create structural fault traps in the uppermost parts of unit T2.
Salt diapirs generate rim synclines within the pods as it grows. These rim synclines generate stratigraphic traps for accumulation within the pods they are often tilted and pinch out towards salt. Rim synclines are vastly distributed within the sedimentary pods and generated traps throughout the entire study area. Structural and stratigraphic traps are illustrated in the conceptual Triassic reservoir distribution cross section in figure 6-8.

6.2.2 Reservoirs

Reservoir types include arid to dryland fluvial reservoirs as well as possible aeolian reservoirs. Arid fluvial and aeolian reservoirs are the likely common types in Lower Triassic Unit T1. In Upper Triassic Unit T2 dryland fluvial and lacustrine deltaic reservoirs are the present reservoirs. Reservoir architecture range from isolated single channels via multilateral channel complexes to multilateral and multistorey channel complexes. Channel complexes may range from sheetlike units to more isolate asymmetric bodies located within syn halokinetic units (fig 6-5). Within each unit, there is a stratigraphic change from more isolated reservoirs units in the lower part to increasingly wider upwards to the most extensive reservoir architecture in the upper parts. The Heron Cluster producing from the Triassic Skagerrak formation on the UKCS is classified as a high-pressure high temperature (HPHT) reservoir due to deep burial and sediment load (McKie & Audretsch, 2005).

Laterally the reservoir bodies are mostly restricted in minibasins. The lower channel deposits of the entire unit T1 and great portions of unit T2 are located in rim synclines within the pods. The uppermost channel belt deposits of unit T2 are areally extensive and may be connected to other regions, but in all areas they exceed multiple supra salt displacement distorting the connectivity. Figure 5-18 indicate that the channel belts within unit T2 comprise a more multistorey profile, while the underlying unit T1 that have more isolated channel belt deposits.

The best Triassic reservoirs occur where the pods are grounded onto the underlying Rotliegend base forming Triassic highs with little Jurassic strata overlying (Hodgson et al., 1992). Grounded pods are abundant in domain area A and area D, whereas the occurrence of floating pods are found located in domain area B and C (fig. 5-8). This implies that the best-preserved reservoir porosity and permeability are situated within these areas.

The observations of Unit T2 from core analysis of well 7/12-6 imply that massive channels occur at the beginning of the T2 succession. Following this are smaller stacked channels observed in the core. This imply that the depocenter in which the fluvial streams occur becomes less synclinal and more sub horizontal due to halokinetic pulses. The GR log motif shows distinctive sand bodies separated by muddier intervals. The lower sands are massive bodies and correspond to isolated channel deposition, whereas the upper sand intervals are more laterally extensive than the lowermost one (fig. 5-14. The classification of the members of the Skagerrak Formation by P. J. Goldsmith et al. (1995) imply that the lower Judy sandstone comprises massive fluvial channel deposits. The lowermost channels e.g. seen on figure 5-18 indicate deeper massive channel belts in contrast to the two overlying channel massifs. The Joanne and Josephine sands, on the other hand, comprise fine sandstones, where the Joanne also encompasses medium to coarse sand deposited as channel fill.

6.2.3 Seals

Top seal for the Triassic is the Lower Jurassic Fjerritslev Formation ((NPD), 2019a). Intraformational seals seals separating the Lower Triassic Unit T1 and Upper Triassic Unit T2 are assumed present in form of laterally extensive floodplains- playas to marine mudstrones. Where present Unit T1 and Unit T2 forms separated reservois-seal pairs. Top seal may be critical where the Triassic is directly overlain by the Vestland Group. Intraformational seal between Unit T1 and Unit T2 may have a lower competence where there is a high proportion of carboantes.

Finally, floodplain mudstones may form intraformational seals within each of the Triassic units, resulting in stacked play zones within each reservoir seal pair. Intraformational seals of the Skagerrak Formation are defined by three intervals of floodplain deposition. The Skagerrak Formation comprise tree mudstone members; Julius, Jonathan and Joshua that act as potential intra formational reservoir seals (Kape et al., 2010). From. Figure 5-14 and 6-5 display levels of sand stratigraphy which may be correlated to the sand and mud intervals of the Skagerrak Formation (Kape et al., 2010).

6.2.4 Source Rocks

The source can be of subsalt origin and have migrated updip the subsalt thick skinned fault through zones of grounded sedimentary pods. A potential Triassic fault may be hard linked (fig 5-2) to the subsalt faults within the western section of the study area. The intra Triassic marker may constitute a source rock as the GR reading imply shale and they might be a result of lacustrine prolific deposition in isolated minibasins.

The type source rock in the North Sea is the Farsund and Mandal Formations, Upper Jurassic. The source rock migrates to different aged reservoirs and is the proven source for Permian Auk and Argyll fields in the UK quadrant 30 by migration up dip from the Central Graben area (Glennie et al., 2003). Up dip migration from the Central Graben area may be a potential migration path for the westernmost parts of area B and D. The Embla Field located on block 2/7 is a pre-Triassic reservoir located in the Central Graben area. The Embla field is sourced by oils migrating from the Mandal and Farsund formations source rocks, Upper Jurassic, and proves the possible migration into older aged reservoirs (Knight et al., 1993).

The Sørvestlandet High restricts migration from the Central Graben areas to the Norwegian Danish Basin as hydrocarbons migrate up dip. Potential sources located in the NDB basin areas a more preferable for a hydrocarbon generation within the basin, than a long distance migration due to basin margin uplift (fig 6-8). The source rock for a Triassic reservoir in the NDB are most prone to be of pre-Triassic origin. The Zechstein Group is a proven source in the South Permian Basin (SPB) and within two samples from the Mid North Sea High the Stinkkalk shales is a potential source, albeit noncommercial, the Kupferschiefer Formation can be a source, although proven too thin (Jackson & Stewart, 2017). The Kupferschiefer Formation is a verified type 2 oil-prone source rock from well 25/10-2 in the northern North Sea (Pedersen, Karlsen, Lie, Brunstad, & di Primio, 2006). Upper Carboniferous coals may source the NDB with gas bearing migration, they may be overmature due to deep burial but have been absent due to erosion of the Upper Carboniferous (Bruce & Stemmerik, 2003). Pedersen et al. (2006) suggest that Lower Carboniferous coals are present in the North Permian Basin but that generation and migration took place during Late Paleozoic so for it to be sourcing the Triassic NDB reservoir a tertiary migration is necessary. The Permian and Carboniferous source rock may be candidates for the Lower Triassic Unit T1

The Triassic source potential lacks a great lacustrine flooding event to deposits a great source rock prone shale. Minor minibasins restricted events are more prone in the lower Triassic unit T1, but they are most likely not extensive enough to generate a commercial oil-prone source rocks. The fluvial systems of Triassic unit T2 can provide coal layers that can be gas bearing. Coal is present in the core of well 7/12-6 presented in chapter 5. located at 3434 meters depth in the Skagerrak Formation.

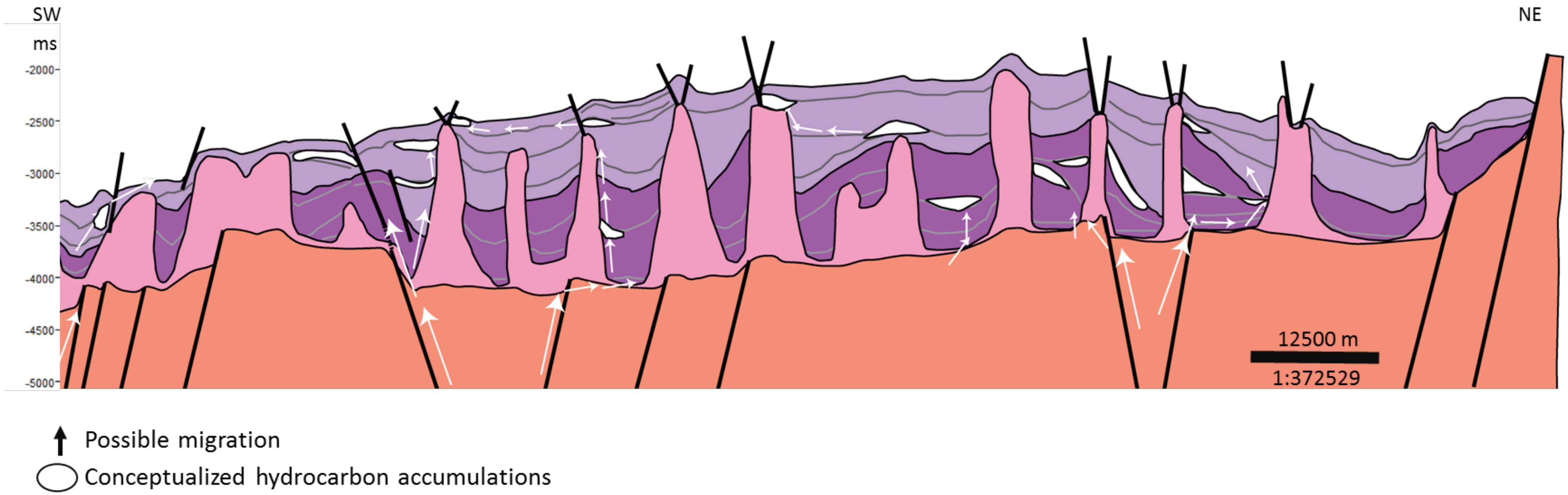


Figure 6-8 Conceptual figure of possible sub salt migration and accumulation of hydrocarbons in the different traps on line A-A' from figure 5-1. The figure assumes a present Permian or Carboniferous source or distance migration of the Upper Jurassic source from the Central Graben.

6.2.1 Play Models

Both Unit T1 and Unit T2 comprise the same source assuming a Carboniferous or Permian source. The Upper Jurassic source it is more prone for the Upper Triassic unit T2 as the migration moves upwards and the salt walls act as barriers for Lower Triassic migration. A third potential source for the upper Triassic unit T2 play model is the intra Triassic marker, a high amplitude contrast event in the seismic data, a mudstone deposition recognized in the well data.

The Lower Triassic traps are salt related and situated in depocenters of rim synclines, turtle structure anticlines and onto salt flanks (figure 6-9). The Upper Triassic Unit T2 traps have the same appearance and style as in the underlying unit but also comprise supra salt traps such as fault-related structural traps and supra salt anticlines. Stratal pinch outs are also potential traps, and the hydrocarbons sitting in isolated channels can be trapped by overlying floodplain deposits.

The reservoir styles in the two units are different. Single isolated channels belt deposits define unit T1 potential reservoirs. Lower Triassic Unit T1 are dominated by single isolated sheet-like channel complexes. The channel units are restricted within the sedimentary pods but may be laterally extensive in the elongated parallel pods of area A. The connectivity decreases towards the western part. Figure 5-114 and 6-5 demonstrate that the Upper Triassic Unit T2 channel belts have higher lateral and stratigraphic connectivity. The lateral connectivity and areally extent increases as the unit shallows.

Unit T1 is capped by a fine-grained sediment surface defined by the intra Triassic marker and high GR log reading. The Middle Triassic flooding disconnects the Triassic megasequences and forms a potential seal rock for the Lower Triassic Unit T1sequence. The salt acts as a bounding surface and seals the base and the sides of Lower Triassic Unit T1 reservoirs. Unit T2 is capped by Jurassic sandstone reservoir and potentially appear as connected reservoirs in these, such as in the Ula and Oda reservoirs. Intraformational seals as the Skagerrak Formation mudstone members may be sealing the lower channel stacks, and intra channel belt floodplain deposits potentially compromise the connectivity within the HPHT reservoirs of the Triassic section.

7 CONCLUSION

7.1 Conclusion

The Triassic succession was subdivided into two megasequences; Lower Triassic Unit T1 and Upper Triassic Unit T2. The units were influenced by different pulses of halokinetic movement as inferred from the rim syncline evolution. Four distinct halokinetic domains were defined based on the salt structuring style and geometry and deformation of adjacent depositional pods. These were used to define different depositional domains and sedimentary architectures within the halokinetic domains.

The initial basin structuring was focused in the eastern part of the study area, the Egersund Basin, and is tentatively dated to earliest Early Triassic. The main Triassic deformation is tentatively dated to the mid-Triassic basin-wide structuring and is expressed as an interval of intensified halokinetic structuring across the entire Norwegian-Danish Basin. During this stage the early formed salt walls were accentuated and some evolved into early stage diapirs. The salt movement paused during deposition of the extensive upper parts of Upper Triassic Unit T2, in the latest Late Triassic. Other important structuring events that impact Triassic prospectivity is post-Triassic (Middle to Late Jurassic) basin margins collapse and Cretaceous to Neogene diapir growth.

Triassic sediment inputs were sourced from the adjacent hinterlands in the north. The main sediment influx was interpreted to be sourced from the north-northeast during deposition of both stratigraphic units. Fluvial systems filled in the inherited salt mini-basins by fill to spill processes eventually producing extensive fluvial systems that extended beyond the study area by the end of Early and Late Triassic, respectively. Within the Norwegian-Danish Basin, the main depocentres of the two units shifted laterally, i.e. the Lower Triassic inferred to have thick accumulations toward the northeastern basin margin whereas the Upper Triassic may have sandier deposits also within the central part of the basin. Laterally extensive fluvial reservoir units are likely present in the upper part of the two seismic units.

The Triassic play models comprise the existens of a long distance migration of the Upper Jurassic source rocks from the Central Graben. The source rock for the Triassic play can also be from an underlying gas bearing Paleozoic source rock. The reservoirs mostly sit in traps generated by the salt structuring or stratigraphic traps generated by the fluvial systems.

Common traps are salt induced stratigraphic anticlines and pinch outs in the fluvial formations in the rim synclines The reservoir seal pairs are 1) sheet flood sandbodies in the Lower Triassic Unit T1 capped by the muddy floodplain boundary between the two units. 2) Upper Triassic fluvial sandstones capped by intraformation floodplain muds or as a connected reservoir to the Vestland Group. Triassic reservoirs are fine to coarse grained fluvial deposits buried at depth generating High Pressure high temperature reservoirs.

7.2 Further Recommendations

In order to better constrain the tectonostratigraphic evolution of the Triassic succession in the Norwegian Danish Basin in a coherent source to sink manner, it is recommended to provide a detailed provenance study based on cored intervals in the Norwegian sector.

It is also highly recommended to provide detailed regional restorations of the Central North Sea. Regional restorations should be undertaken to detail the basin evolution. Detailed regional restoration will establish the early onset basin structuring during the Triassic to detail. This is important to understand the early onset basin evolution. The early onset basin evolution may provide information on trap formation and accumulation of hydrocarbons for petroleum prospectivity.

New 3D datasets provide a new and improved data source with higher resolution and fidelity of the Triassic succession. It is therefore recommended to utilize these datasets to provide a detailed 3D interpretation of the reservoir units along the margins of the Norwegian Danish Basin.

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APPENDIX

Appendix 1: Full core interpretations of core 7/12-6 provided by Aker BP.

REGIONAL STUDY OF THE SKAGERRAK FORMATION IN THE NORWEGIAN CENTRAL GRABEN

SEDIMENTOLOGICAL CORE LOG	SCALE: 1:50
WELL: 7/12-6	FIGURE

CHEMOSTRAT®

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LITHOLOGY
- BRECCIA
- CONGLOMERATE
- SANDSTONE
- SILTY SANDSTONE
- SILTSTONE
- MUDSTONE
- COAL
- LIMESTONE
- ANHYDRITE
- M MASSIVE
- R RUBBLE
- INTRACLASTS
- ARGILLACEOUS
- CARBONACEOUS
- PEBBLY
- m MICACEOUS

BEDDING CONTACTS
- SHARP
- EROSIONAL
- LOADED/DEFORMED
- BIOTURBATED
- TRANSITIONAL

BIOGENIC STRUCTURES
- ROOTLET TRACES
- BIOTURBATION - HORIZONTAL
- BIOTURBATION - VERTICAL
- BIOTURBATION - CHURNED
- PLANT FRAGMENT

SEDIMENTARY STRUCTURES
- HORIZONTAL STRAT.
- CROSS-STRAT.
- TROUGH X-STRAT.
- CURRENT RIPPLES
- WAVE RIPPLES
- WATER ESCAPE/INJECTION
- SLUMPED BEDDING
- LOADED
- PCL PRIMARY CURRENT LINEATION
- WATER MODIFICATION/RAINPRINTS
- WIND REWORKING
- DESICCATION CRACK

SECONDARY STRUCTURES
- OPEN FRACTURE
- PARTIALLY CEMENTED FRACTURE
- CEMENTED FRACTURE
- FRACTURE WITH VISIBLE DISPLACEMENT
- NODULES
- MICRONODULES
- CONCRETIONS
- BS BRECCIATED SEDIMENT
- REDUCTION SPOT
- PERVASIVE CEMENT
- An ANHYDRITE
- Cal CALCITE
- Dol DOLOMITE
- Py PYRITE
- Si SILICA
- rh RHIZOCRETION
- cap CAPILLARY ZONE CARBONATE
- gwc GROUNDWATER CARBONATE