DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/33**

Capture, Storage and Use of CO_2 (CCUS)

Seismic interpretation of existing 2D and 3D seismic data around the Havnsø structure (Part of work package 5 in the CCUS project)

Ulrik Gregersen, Henrik Vosgerau, Shahjahan Laghari, Kenneth Bredesen, Rasmus Rasmussen & Anders Mathiesen

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Preface

Late 2019, GEUS was asked to lead research initiatives in 2020 related to technical barriers for Carbon Capture, Storage and Usage (CCUS) in Denmark and to contribute to establishment of a technical basis for opportunities for CCUS in Denmark. The task encompasses (1) the technical potential for the development of cost-effective CO_2 capture technologies, (2) the potentials for both temporary and permanent storage of CO_2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO_2 usage potentials, including business case for converting CO_2 to synthetic fuel production (PtX). The overall aim of the research is to contribute to the establishment of a Danish CCUS research centre and the basis for 1-2 large-scale demonstration plants in Denmark.

The present report forms part of Work package 5 (Validation of storage complexes) and focuses on a structural and seismic stratigraphic study around the Havnsø structure using wells and seismic ties from the Stenlille structure. The Havnsø structure is located near the town of Havnsø and into the southern Sejerø Bugt, geologically in the eastern part of the Danish Basin (Fig. 1).

Contents

Dansk opsummering

Denne undersøgelse omfatter en seismisk stratigrafisk tolkning og kortlægning af horisonter og forkastninger i Gassum og Fjerritslev formationerne i Stenlille og Havnsø strukturerne. Havnsø strukturen er en stor aflang NW – SE strygende strukturel fire-vejs lukning og Stenlille er en mindre SW – NE strygende struktur på top Gassum Formation (top reservoir) niveau og i den overliggende Fjerritslev Formation (hoved forsegling). Havnsø strukturens toppunkt ligger lidt syd for Havnsø tæt ved kysten, mens strukturens saddelpunkt mod syd ligger omtrent halvvejs mod Stenlille strukturen baseret på analyse af de nuværende data. Gassum og Fjerritslev formationerne er begge en del af strukturerne, som primært er dannet pga. hævning af underliggende salt puder, og formationerne er gennemsat af mindre SW – NE orienterede forkastninger, der er dannet under saltbevægelserne og den midt-Kimmeriske tektoniske fase i Jura tid. Der er gennemført en omfattende tolkning af seismiske data med boringskorrelation af formationer og sekvensstratigrafiske flader og enheder i Stenlille strukturen. Gassum formationen afspejler i Stenlille området primært sand-rige aflejringssystemer fra lavmarine til kystnære og fluviale miljøer. Formationen overlejres af den mudderstens dominerede Fjerritslev Formation, der indeholder mindre sandlag, og generelt afspejler marin aflejring og på dybere vand end i Gassum Formationen. Sekvenser og seismisk facies er forsøgt korreleret til Havnsø strukturen, men en meget ringe kvalitet og opløselighed af de eksisterende seismiske data umuliggør dette. Korrelationen til Havnsø strukturens offshore del ude i Sejerøbugten er yderligere kompliceret af hældende skannede seismiske linjer, der medfører mis-ties mellem linjerne. Dette er kritisk, da denne del udgør den nordlige del af strukturen, og det påvirker de tolkede horisonter og dermed dybdekortene og de lukkende konturer af strukturen (spill-point). Reprocessering blev testet på nogle af disse seismiske linjer; kvaliteten blev forbedret og muliggjorde en regional seismisk tolkning af formationsgrænser, samt få sekvensstratigrafiske horisonter (flooding flader) og forkastninger. Gassum Formationen bliver generelt tykkere ud omkring Havnsø strukturen. Den sandstens-rige nedre del af formationen i Stenlille under den transgressive flade TS5 har varierende tykkelse, men ser ud til at have nogenlunde ensartet tykkelse til Havnsø strukturen, hvor den dog lokalt bliver tyndere ved toppen af strukturen. Særligt i den øvre del af Gassum Formationen er det muligt, at sandstenslagene bliver tyndere og færre, og mudderstensintervallerne tykkere som følge af en mere marin, kystfjern position på aflejringstidspunktet i Havnsø området sammenlignet med Stenlille området.

Summary

This study presents a seismic stratigraphic interpretation and mapping of key horizons and faults of the Gassum Formation and Fjerritslev Formation in the Stenlille and Havnsø structures in the western Zealand and the Sejerø Bugt. The Havnsø structure is a large elongated, NW – SE trending four-way dip structural closure and the Stenlille structure is a smaller SW – NE trending four-way dip structural closure, at the top Gassum Formation (top reservoir) level and in the overlying Fjerritslev Formation (main seal). The top point of the Havnsø structure is located onshore near the coastline just south of Havnsø based on the currently available data. The saddle point of the structure is located approximately mid-way to the Stenlille structure. Both the Gassum and Fjerritslev formations are parts of these structures, which are mainly caused by underlying salt pillows and affected by minor SW – NE trending faulting. The Jurassic mid-Cimmerian regional tectonic phase probably contributed to the development of the structures with compressional tectonics and faulting. A detailed interpretation with well ties of formations and sequences is carried out in the Stenlille structure. In the Stenlille area, the Gassum Formation comprises mostly fluvial-deltaic, fluvial-estuarine, near-coastal and shallow marine sandstones, intercalated with lagoonal or offshore mudstone and heterolithic intervals. The formation is overlain by the mudstone-dominated Fjerritslev Formation. The sequences and seismic facies are attempted correlated towards the Havnsø structure, but due to very poor seismic data of low resolution a detailed interpretation and correlation is not possible. The challenge of correlation into the offshore part of the Havnsø structure into the Sejerø Bugt is furthermore complicated by dipping scanned seismic sections, which cause mis-ties along the sections. This is critical as this area is the northern part of the Havnsø structure, and as it will affect the interpreted horizons and thus the depth maps and closures (spill-point). Reprocessing was tested on selected lines and provided basis for regional correlation of formation boundaries, and a few sequence stratigraphic horizons (flooding surfaces) and faults. The general trend is that the Gassum Formation thickens westwards in the Havnsø structure area, but the sandstone-rich lower part of the formation in Stenlille (below the transgressive surface TS5) appears to have a relative constant thickness towards Havnsø with local thinning over the top of the structure. Especially for the upper part of the formation, it is possible that sandstone intervals become thinner and less in number on the behalf of thicker mudstone intervals due to a more offshore position in the Havnsø area compared to the Stenlille area at the time of deposition.

Introduction

In order to provide basis for estimation of the storage potential of CO_2 in the Gassum Formation of the Havnsø structure, a structural and seismic stratigraphic study was carried out near the town of Havnsø and offshore in the southern Sejerø Bugt. The mapped region covers the Stenlille to Havnsø and Sejerø Bugt areas (Fig. 1). Four main surfaces are mapped at formation boundaries: Base Gassum Formation (Top Vinding Formation), Top Gassum Formation, Top Fjerritslev Formation and Base Chalk Group. Geologically, this area is located in the eastern part of the Danish Basin, north of the Ringkøbing−Fyn High and south of the Sorgenfrei-Tornquist Zone (Figs. 1 and 2). The study aims primarily at defining the size and type of the Havnsø structure. Furthermore, sequence stratigraphic surfaces, seismic facies and faults were studied and described in both the Stenlille area covered by 3D seismic data and the Havnsø area in order to compare and correlate the areas. The aim is also to give input for other studies including reservoir simulation.

1 Database

The database of the study area is shown in Figures 3A and 3B and comprises the Stenlille-97 3D seismic survey and the eight 2D seismic surveys: DN87O (reprocessed) and DN94O (reprocessed), SSL6267, SSL7273 (all onshore) and the offshore surveys GSI75B, PRKL74A, PRKL80B and 2D test lines (‘Røsnæs-2D-testlines’). The line grid spacing between the 2D seismic lines is large, mostly c. 3 − 5 km, but in some areas, the spacing is more than 5 km and in the Stenlille area less than 20 m. The database comprises twenty wells from the Stenlille area: Stenlille-1 to Stenlille-20 (ST-1 to ST-20; Fig. 3B). In addition, the Terne-1 well in Kattegat, more than 50 km north of Sejerø and closer to the basin margin (Fig. 1), is used for offshore correlation to the Sejerø Bugt (Fig. 3A). The most comprehensive well data set is available from the Stenlille-19 well with many log types, Vs, Vp and check-shots, providing a valid time-depth relation. These data are used for synthetic seismograms and seismic to well tie (Section below: Seismic interpretation and well ties based on Stenlille data; see also Bredesen 2020). The Stenlille-1 well is close to 2D seismic tie lines towards the Havnsø area (Fig. 3A) and many logs are also available from this well. Thus, these two wells (ST-1 and ST-19) are the key-wells used for well ties to the interpretation of the 2D and 3D seismic lines. The database for this study was provided in a workstation project with Petrel © software (version 2017.4).

2 Data quality

The quality of the seismic data is highly variable from good to very poor (Figs. 3A and 4). The 2D and 3D seismic data in the Stenlille area are generally of good quality and are all digital data (Fig. 4A). Most of the used 2D seismic surveys west of the Stenlille area and in the Sejerø Bugt are generally poor to very poor in quality and are nearly all scanned data (Figs. 3A and 4). The key seismic survey (PRKL74A) offshore over the Havnsø structure in the Sejerø Bugt is a scanned survey of poor quality (Fig. 4B). The seismic survey SSL6267 is the key onshore survey over the Havnsø structure with important tie lines to the Stenlille area. This survey is a scanned survey of very poor quality (Fig. 4C). The poor to very poor data over the Havnsø structure significantly reduces the opportunity for valid seismic interpretation. Lines from each of these key surveys were reprocessed to test for possible improvements (see the reprocessing section below). The seismic interpretation from the Stenlille wells towards the Havnsø area is not only hampered by poor data, but also by data mis-fit (mis-ties) of seismic lines. Mis-tie between seismic lines are found many places in the available database between the 3D seismic survey and 2D lines in the Stenlille area, at tie connections from the Stenlille area to 2D lines west of Stenlille, and within the Sejerø Bugt (see the mis-tie analyses section below). Local faulting at line connections and at the end of lines also disturbs the seismic line ties, as in the SE and NW parts of the Stenlille 3D area and in the southernmost Sejerø Bugt. In addition, the interpretation offshore is difficult due to uncertain correlation on poor data to wells far away. The closest located offshore well from the Sejerø Bugt with seismic line connections is the Terne-1 well, but it is located more than 50 km north of the Havnsø structure (Fig. 1). The seismic tie to the well is challenging due to poor data, but also as seismic interpretation of horizons has to cross the complex Sorgenfrei-Tornquist Zone, where the well is located (Fig. 1). The correlation from the Havnsø area onshore across the coast and into the Sejerø Bugt surveys is also difficult due to the data gap and faults at the end of lines in the southernmost Sejerø Bugt. The large line grid spacing on poor data makes seismic interpretation difficult and thus uncertain regarding horizons, faults, seismic features and facies connections due to the large jumps in data points.

2.1. Mis-tie analyses

Vertical mis-ties between the signals for intersecting 2D lines both between lines of same survey and between lines of different surveys are observed. Mis-ties are in some cases observed as differences of up to two to three reflections. A detailed mis-tie analysis for the seismic data was carried out in Petrel. The Petrel-mis-tie analysis is here categorized into:

- Qualitative (visual) mis-tie screening
- Quantitative mis-tie screening

Qualitative (visual) mis-tie screening

First, a visual mis-tie analysis was carried out between the intersecting 2D surveys and the reference 3D seismic survey (Stenlille). A first order qualitative analysis depicts that 2D seismic lines show signal discontinuity (breaks) within a survey, along other intersecting 2D surveys and along the 3D seismic data. Dataset was broken down into smaller regions and initial mis-tie was visually screened along the following data between 800 to 1500 milliseconds TWT:

- Stenlille-97 3D and the two 2D surveys over the area: DN87O and DN94O
- DN87O, DN94O and the PRKL6267 surveys to the west
- Offshore between surveys GSI75B and PRKL74A (Fig. 3A)

It was found that a dynamic mis-tie exists in the study area between seismic data from Base Chalk Group down to Base Gassum Formation. Fourier analysis of seismic data reveals that the content of high frequencies is highest in Stenlille-97 3D seismic data, which is the most recent dataset. Therefore, this 3D seismic survey is used as the reference seismic dataset and 2D lines are adjusted to this survey. Another reason to use 3D seismic data as reference is that the higher resolution has allowed more reliable well-seismic ties. Thus, in all maps over the Stenlille area only interpretations from the Stenlille-97 3D survey are used. Overall, the vertical misfit between seismic signals is of order approx. 10−20 milliseconds (TWT), however, locally vertical misfits larger than approx. 30 milliseconds (TWT) are also observed. The Stenlille-97 3D survey is ~10−20 milliseconds shallower than lines of the DN87O and DN94O surveys (Fig. 4A). Data mis-ties unfortunately also occur at ties from the 3D survey area and NW towards the Havnsø structure, and are visual on the intersecting seismic sections between DN94_D07 and R4_1 part 2, which are apparently ~30 ms TWT deeper. The challenge here is that if the DN94O survey is adjusted ~15 ms up to fit the 3D survey (see Fig. 4A), then the mis-fit to the R4 survey (and other sections that tie westwards) will increase to ~45 ms TWT. Thus, more work including acquisition of new data is needed to sort out which surveys should be adjusted.

Some of the vintage seismic data include scanned seismic lines with a very poor signal to noise ratio and a very low frequency content adding to more complexity of the mis-tie analysis. Vertical mis-ties are found in the offshore surveys PRKL74A and GSI75B, both between the surveys (e.g. section 74_309 and the ~20 ms TWT deeper line K75024 northernmost in the Sejerø Bugt; Fig. 5) and between lines of the same survey. The order of vertical misfit of the sections is also here mostly ~10−20 ms TWT. The problem is complicated as it has turned out, that some of the sections apparently dip, when the horizontal workstation timelines are compared to the timelines of the scanned seismic profiles (Fig. 5). The dipping seismic sections cause increased mis-ties along the sections. This is critical as this area is the northern part of the Havnsø structure and as it affects the depths of the mapped horizons and thus the map closures and top definitions.

Quantitative mis-tie screening

Petrel Mis-tie Manager is used to generate tables and quantify the mis ties between intersecting seismic lines with reference to the Stenlille-97 3D seismic survey. The Petrel Mis-tie Manager is an interactive tool for managing vertical, gain, and phase mis-ties and corrections between 2D/3D seismic lines. It was used here to calculate and specify mis-ties. The procedure is briefly described in Appendix 1A. Analyses were performed: (1) in the Sejerø Bugt (Fig. 6; Appendix 1B) and (2) in the Stenlille 3D survey area, between the DN87O, DN94O and the Stenlille-97 3D surveys (Figs. 7 and 8; Appendix 1C). As a test to correct for the mis-ties the intersecting lines were applied with constant as well as with dynamic shifting. As discussed previously the nature of the mis-ties between 800 to 1500 milliseconds TWT is quite variable, therefore best corrections are observed with a dynamic operator that varies along the length while removing mis-ties. However, the pitfall to this strategy is that this can also introduce severe signal stretch.

Conclusion of the mis-tie analyses

In conclusion, the visual mis-tie screening and the Petrel mis-tie analysis show that there are data mis-ties between different seismic surveys, but also between lines of the same surveys in the order of mostly approx. 10−30 ms TWT. Some of the mis-ties requires a dynamic shift (gradual time shifts stretching the data) on the same line to make a full fit at crossing seismic sections, and thus this is not straight forward and is omitted here. In the Sejerø Bugt, the reasons for the variable mis-ties following the same seismic section include dipping scanned lines. In the Stenlille area it may be related to other factors including different parameters and e.g. the time of acquisition with different amounts of gas storage since 1991, which likely affects the seismic signals differently. However, this has not been studied further in this project. Mis-tie corrections for the surveys were not applied to the original files of the project database, as it was not possible within the frame of this study to sort out all mis-ties and adjust surveys properly. However, the mis-tie problems and magnitudes are described here for future consideration. New data of higher quality with direct ties between wells in the Stenlille area and the Havnsø structure would be important to contribute to sort out the mis-fit of the older data and optimize correlation of formations and sequence surfaces.

2.2. Reprocessing test of three seismic sections across the Havnsø structure

Due to the poor to very poor data quality of 2D seismic sections across the Havnsø structure, it was decided to test if reprocessing could improve the data quality to achieve better continuity and resolution. The used software, seismic sections and main steps in the reprocessing are briefly described below.

The reprocessing trials have all been done by the ProMAX 2D processing software available at GEUS. The three 2D seismic sections reprocessed are: 74_303 of survey PRKL74A, SSL73_038 of survey SSL7273 and R4_1 of survey PRKL6267 (Fig. 9; Appendix 2). Line 74_303 and R4_1 only exist as scanned version of the original paper sections. The scanned data have been archived in standard SEG-Y format, but basically each sample from the scanned paper section consists of black/white pixel values.

To obtain improvements in data quality the first step in the reprocessing was to simplify transformation from black/white pixel values to standard seismic trace amplitude response. After this transformation dipping noise have been filtered using standard FK dip filtering followed by a dip scan filter enhancing coherent events. The transformation from scanned sample values to standard seismic trace amplitude response is considered a very important step in obtaining further improvements in data quality from reprocessing. More sophisticated software for this transformation is available at external providers having this specialized service, and for future reprocessing work of key lines, it is suggested to include this more costly and time-consuming approach.

Final stack archive data for line SSL73_038 is the only version of this line available for the reprocessing trial. Like the two scanned lines FK dip filtering followed by a dip scan filter for enhancing coherent events was found to improve the quality of main horizons. Finally, a spectral whitening filter was applied in order to slightly improve the frequency content. In general reprocessing of data from the 1960's and 1970's to some extent have potential for improvements in quality of seismic horizons and to some extent also for seismic resolution. However, regarding more detailed internal studies of seismic facies changes etc. improvements from reprocessing of these old vintage datasets in general are marginal.

3 Results

3.1. Seismic interpretation and well ties based on Stenlille data

Seismic horizons – definitions and well ties in the Stenlille-97 3D survey

The main horizons interpreted in this study are: Base- and Top Gassum and Top Fjerritslev (Fig. 9). These horizons provide the depth-structure surface maps and thickness (isochore) maps of the Gassum Fm reservoirs and the Fjerritslev Fm main sealing successions. The Base Chalk has been interpreted for constraining structures, mis-ties and depth conversion. In addition, sequence stratigraphic boundaries were interpreted, mainly within the Stenlille 3D area. All four formation boundary horizons were interpreted on every 10th (or more) inlines and cross lines in the Stenlille-97 3D survey. In addition, five faults were interpreted in the SE part of the survey. The interpreted horizons and faults were transferred and used also in the work of Vosgerau et al. (2020).

The seismic horizons are interpreted following standard seismic stratigraphic methodology including identification of onlap, downlap, truncation etc. of reflection configuration and successions identified by different seismic facies. The horizons are also based on well tie in the Stenlille area, in particular to the Stenlille-19 well (Figs. 10−13). Lithostratigraphic and sequencestratigraphic well-log boundaries (well-tops) are adjusted by time/depth relations to the seismic data. A synthetic seismogram of the Stenlille-19 well (Fig. 10) is used to constrain the seismic interpretation as this well is considered to have the most reliable time-depth relation in the Stenlille area.

Base and Top Gassum

The Gassum Formation is the main reservoir formation, and results from mapping gives input of depths, thicknesses, and faults relevant for reservoir models and other related work, in order to assess the CO_2 storage potential. Correlation and discussion of facies give input to considerations of the sedimentological reservoir model to be defined in other parts of the project. The Gassum Formation is a proven reservoir containing several reservoir zones (Fig. 12; Kristensen 2020) in the Stenlille structure, where gas since 1991 has been stored in the upper reservoir zones with occasional tapping for customer use (see https://gasstorage.dk/). Twenty wells have been drilled in the Stenlille structure (Fig. 3B) and the Gassum Formation is thus a well-known, working reservoir with multiple reservoir/seal zones and sealed with a thick mudstone dominated succession of the Fjerritslev Formation.

Figure 10 shows a well-tie and synthetic seismogram based on the Stenlille-19 well, with panels left-to-right showing P-velocity (Vp), S-velocity (Vs), density (Rho), acoustic impedance (AI), synthetic traces and a 2D seismic cross-section along the Stenlille-19 well path.

In Figure 10A the blue and red horizontal lines represent well tops for Base- and Top Gassum, respectively. See also the quantitative seismic interpretation of the Gassum Formation in Bredesen (2020). The synthetic seismogram correlates to the 2D seismic section to the right, where the Base- and Top Gassum are interpreted.

Some key observations and implications (Fig. 10A):

- The Base Gassum interface is characterized by a minor drop in velocities (Vs) and an increase in acoustic impedance (AI) giving a black peak both in synthetic traces and on the seismic section. Thus, it was decided to interpret the Base Gassum in the black reflection (on black-grey-white color table/or a red reflection on continous colortable 332) in both 3D and on 2D seismic data (Figs. 10 and 13).
- The Top Gassum exhibits a weak increase in velocities and acoustic impedance, which corresponds to a white trough in the synthetic seismic and fit with a white trough in the seismic section (right) at the well-top. In the 3D seismic data this white trough occurs below a double peak. Thus, it was decided to interpret the Top Gassum in the white reflection (on black-grey-white color table/or a black reflection on continous colortable 332) in the 3D seismic data and on 2D data (Figs. 10 and 13).

Top Fjerritslev and Base Chalk

Figure 10B shows a well-tie and synthetic seismogram based on the Stenlille-19 well with the same panels as in Figure 10A. The Vp and Rho logs are despiked where the original logs are shown in a thick transparent curve and with a smoothed (or upscaled) curve in the middle that is easier to interpret in terms of contrasts in velocities, density or acoustic impedance at a seismic scale. The green and pink horizontal lines represent well tops for Base Chalk and Top Fjerritslev, respectively.

Some key observations and implications (Fig. 10B):

- The Top Fjerritslev exhibits a weak increase in velocities and acoustic impedance, which would correspond to a white trough in the synthetic seismic.
- The Base Chalk interface is characterized by a significant drop in velocities and acoustic impedance that should clearly stand out from the other reflection events in the seismic. In the synthetic seismogram the Base Chalk is shown as black peak.
- The Lower Cretaceous unit is thin in Stenlille-19 (i.e. the interval between the green and purple horizontal lines). Hence, it is possible that the strong reflection event from the Base Chalk interferes with the amplitudes from the Top Fjerritslev reflection event. Consequently, it can be more difficult to determine whether to interpret Top Fjerritslev on a peak, trough or a zero-crossing event.
- There is a clear mis-tie between the Base Chalk event on the synthetic and real seismic data due to an inaccurate time-depth relationship around this interval. A possible explanation is that there are some inaccurate datapoints in the Stenlille-19 check-shot data in the zone between Base Chalk and Upper Jurassic. Therefore, a more throughout well-tie procedure is proposed where the checkshot data is quality checked and where the time-depth relationship is adjusted accordingly to obtain a better tie to the Base Chalk event. The blue stippled lines show a possible correlation between the synthetic and the seismic section.
- The Base Chalk well top derived from log analysis is set at 1234 m whereas the maximum seismic amplitude occurs at 1238 m, i.e. a 4 m difference. The exact depth of the Base Chalk interface is debatable as the drop in velocities and acoustic impedance occurs gradually between 1230−1243 m MD, but the seismic interpretation should anyway be based on the maximum amplitude event.

Interpretation of the Top Fjerritslev: In the 3D survey it was decided to follow the strong white trough(on black-grey-white color table/or a black reflection on continous colortable 332) just below the purple line as this reflection is very strong and continous within the 3D survey (Fig. 10B). However, outside the 3D survey, correlation becomes very difficult as the clear white trough disappear on the poor data and the overlying black peak is better to track regionally due to stronger amplitudes and more clear onlap (Figs. 9, 20 and 21). This horizon (red on the continous color table) is also a prominent onlap surface in the 3D survey (Fig. 8: at 800 ms TWT). The Top Fjerritslev Formation is an erosional unconformity that apparently correlates to a major hiatus revealed in the Stenlille wells, where the youngest preserved parts of the Fjerritslev Formation are lower Toarcian successions of the FIII member (Fig. 31 in Nielsen 2003). Thus, it seems that parts of the FIII and FIV members are missing in both the Stenlille area and the Havnsø area and the erosional top of the Fjerritslev Formation may be correlated to the regional “base Middle Jurassic unconformity” or “Mid-Cimmerian Unconformity” (Fig. 2) identified in most of the basin (Nielsen 2003).

Interpretation of the Base Chalk: It was decided to follow the strong black, continous reflection (on black-grey-white color table/or a red reflection on continous colortable 332), that can clearly be followed both in 3D and on poor 2D seismic sections (Figs. 9 and 20).

Other seismic horizons

The sequence stratigraphic surfaces, including sequence boundaries (SB), transgressive surfaces (TS), and maximum flooding surfaces (MFS), are identified in wells in the Stenlille area (Figs. 11 and 12) and mapped on 3D data in Vosgerau et al. (2020). The sequence stratigraphic horizons were used in this study and further interpreted on selected 2D and 3D seismic lines (e.g. Figs. 13 and 14) and correlated west of the Stenlille area towards Havnsø (see below).

Facies, features and faults of the Gassum Formation in the Stenlille area

Observations

In the Stenlille area the Gassum Formation is reflected in 2D and 3D seismic sections as reflective packages with continuous to discontinuous reflections with local mounds and trough features, transected by numerous minor faults (Figs. 13−16). One of the thickest mounds/thick reflectors comprises the lower part of Sequence 5, between sequence boundary 5 (SB 5) and the transgressive surface 5 (TS 5) from well-log ties (Fig. 13). The lower boundary of the same Sequence 5 (SB 5) cuts down into the underlying Sequence 4 in more places (Figs. 13 and 17; see the arrows). Similar features are also observed in Sequence 6, and to a less extend in Sequence 4 (Fig. 13).

Interpretation

Some of the mounds correspond to stacked sandstone bodies, in particular from lower parts of the sequences between SB and TS surfaces, and these parts probably correspond to deposition during low or slightly rising relative sea level. Wells of the Stenlille area have cored sections (e.g. Stenlille-1, -19: thick black vertical lines in Fig. 12) and have been interpreted in other publications (e.g. Nielsen et al. 1989; Hamberg & Nielsen 2000). The overall depositional environment in major parts of the Stenlille-1 well has been interpreted as dominantly tidal with stacked barrier island deposits overlain by regressive tidal flat sequences, capped by a transgressive sequence with marine mudstones (Nielsen et al. 1989). The lower part of the present Sequence 6 has been interpreted as sharp-based shoreface sandstones with tidal channels formed by a stepwise forced regression (Hamberg & Nielsen 2000). However, the depositional environment in the Stenlille area is currently being studied and revised in other parts of the CCUS project. Sedimentological interpretations of cores from the Stenlille wells as well as palynofacies analysis of core samples thus indicate that fluvial-deltaic and fluvial-estuarine sediments also may form a major component in the Gassum Formation, especially in the lower part of Sequences 4 and 5 (Hovikoski & Pedersen 2020; Lindström 2020). These interpretations are supported by 3D seismic data, that in places show meandering troughs/channels, e.g. near the SB 5 (Fig. 16C). Thus, it is likely that some of the troughs interpreted at the base of some of the sequences could also be fluvial channels. These new results are also discussed in the detailed interpretation of the 3D seismic survey given in Vosgerau et al. (2020).

Some of the faults in the Gassum Formation, at the Top Gassum surface were mapped from the 2D and 3D seismic data. The interpretation shows that faults (F1 – F5) mainly strike NE – SW (Figs. 14 and 15). Correlation with attribute maps also support this strike of the faults (Fig. 16). The Gassum Formation is mostly displaced with its thicknesses being kept (Fig. 15), except for some places where compression possibly have deformed the formation. Most of the faults continues up through the Fjerritslev Formation and they are most likely not syn-sedimentary with the Gassum Formation.

Facies, features and faults of the Fjerritslev Formation in the Stenlille area

Observations

The Fjerritslev Formation is in the Stenlille area generally less reflective on the seismic data than the Gassum Formation, but a few strong seismic reflections are observed at its base, near TS 9 and MFS 9 (Figs. 13 and 14). A number of subtle faults are also observed in the Fjerritslev Formation (Fig. 15).

Interpretation

The Fjerritslev Formation is mudstone dominated (Figs. 12 and 13) with thin sandy layers and correlation with seismic data indicates that the mudstones are generally characterized by low to moderate reflectivity (probably due to low density/velocity contrasts) compared to the more reflective succession of the Gassum Formation (Figs. 10 and 17). The few stronger reflections e.g. near the base of the Fjerritslev Formation at/above TS 9 (Fig. 13), can in some cases be correlated to interfaces with minor variations in gamma ray and velocity values, possibly caused by mudstones with minor sandy layers.

The subtle faults can mostly be tracked in the Gassum Formation and through the Fjerritslev Formation and a few of them continue above the Top Fjerritslev Formation (Figs. 15, 17 and 18). Thus, it is concluded that the faults were mainly formed at the time of formation of the Top Fjerritslev Formation or shortly after. The faults are mostly normal faults, but many of them have also compressional and transpressional elements (Fig. 15): Small parts of reflections/sections have been pushed up and flower structures are interpreted and rooted above the flanks of the salt pillow (Figs. 15 and 17). Thus, the faults are related to the evolution of the salt pillow at the base of the structure and probably regional tectonism involving compression/transpression.

3.2. Extrapolation of Stenlille data to the Havnsø area

In order to optimize the interpretation of the expected Gassum Formation reservoir successions and overlying main seal succession of the Fjerritslev Formation, interpretation of Stenlille data, including seismic horizons, facies and features, are extrapolated to the area of the Havnsø structure. The formation boundaries and internal sequence stratigraphic horizons were interpreted on 2D and 3D seismic sections in the Stenlille area (see above) and correlated west of the Stenlille area towards the Havnsø area (Figs. 17−21).

Gassum Formation

The Base Gassum and Top Gassum seismic horizons are defined on seismic 2D and 3D seismic sections with well ties in the Stenlille structure (Figs. 10−13). The formation section and its base and top are correlated to the 2D seismic sections towards the Havnsø structure, but the poor data and mis-ties in the 2D surveys cause uncertain correlation/interpretation (see Chapter 2. Data quality). However, the Gassum Formation is mostly a more reflective seismic package than the Fjerritslev Formation (Figs. 18 and 21). Top Gassum is interpreted below as a continuous, strong amplitude reflection that can be tracked in nearly all of the mapped area (Figs. 13, 17−22). Thus, the Gassum Formation can be extrapolated west of the Stenlille area and into the Havnsø to Sejerø Bugt area, although the interpretation is uncertain. The Base Gassum was correlated into the Havnsø area but was in some areas a weaker reflection than the Top Gassum reflection.

A detailed sequence stratigraphic interpretation with seismic facies/features (mounds, channels) was attempted correlated to the Havnsø area for the Gassum Formation. However, this is not possible with the present poor seismic data, as shown in Figure 17. It was not even possible to make a detailed seismic interpretation on the reprocessed data, such as in the upper left section of Figure 17 and on the three left sections in Figure 20. Regionally, only main horizons could be tied, including formation boundaries and a few internal sequence stratigraphic horizons: The Transgressive Surface 5 (TS 5) of the Gassum Formation and the Maximum Flooding Surface 11 (MFS 11) of the Fjerritslev Formation (Figs. 17 and 20).

The TS 5 horizon was correlated from the Stenlille area and into the Havnsø area (Figs. 17, 18 and 20). In the Stenlille area, TS 5 tops a thick stacked sandstone succession forming the lower part of sequence 5 (Fig. 13) and corresponding to the reservoir Zone 5 sandstones (Fig. 12; See also Kristensen, 2020). Thus, this transgressive surface is important to correlate into the Havnsø area. Correlation suggests that the lower part of the Gassum Formation generally maintains its thickness or slightly increases towards the Havnsø structure (Fig. 20). The formation thins locally in the central parts of the structure and thickens markedly west of the top of the structure (Fig. 20; see also Fig. 32).

The sandstone layers of the Gassum Formation probably become fewer/thinner further basinward from the Stenlille area towards the Havnsø area. The Stenlille to Havnsø sequence and facies evolution of the Gassum Formation is possibly similar (but there the Gassum Formation includes other sequences) to the facies evolution described southwards in NW Jutland by Nielsen (2003: his Figure 20), where sandstone layers thin from NE to SW into the Danish Basin/Himmerland Graben.

Fjerritslev Formation

The base of the Fjerritslev Formation is correlated as the Top Gassum seismic horizon, described above, and was possible to correlate into the Havnsø area.

The maximum flooding surface 11 (MFS 11) ties stratigraphically to the lower part of the Fjerritslev Fm, probably close above thin sandstone intervals, which may tie to the top of member F-Ia (Fig. 2). In the mapped area, MFS 11 is located in the middle to upper part of the preserved portion of the Fjerritslev Formation (Fig. 20).

The Top Fjerritslev is a truncation surface with regional onlap by younger formations such as the Vedsted Formation in the Stenlille area (Figs. 8, 15 and 20).

As in the Stenlille area, the faults in the Havnsø area (Figs. 20 and 21) are subtle and mainly strike NE – SW on both Top Gassum and Top Fjerritslev levels (se maps below). Faults in the Havnsø area are, as in the Stenlille area, mainly normal faults with components of compressional/transpressional indications, and minor flower-structures are developed in the structure (Figs. 15 and 20).

The structural reconstruction with horizon flattening at Top Gassum and Base Chalk (Fig. 23) shows that the Havnsø and Stenlille structures evolved with growth of the salt pillows forming overlying structural doming anticlinals. The formation of the structures was most likely initiated during time of deposition of the Gassum Formation with local thinning over the structures (Fig. 24). However, the structures developed more pronounced at the time of formation of the upper part of the Top Fjerritslev Formation. The thinning of the lower part of the Gassum Formation below TS5 may indicate initial syn-depositional doming within the Gassum Formation sequences. See also Vosgerau et al. (2020) where initial doming is interpreted to have controlled channel positions west of the top of the Stenlille structure (Fig. 16C). Both normal faults and faults with reverse/compressional indications are observed (Fig. 20) and may be caused by the doming and regional compressional related tectonics. Cross sections (Figs. 7, 17 and 20) show that the structures are most developed with steepest anticlinals in the Gassum to Fjerritslev formations, and that the Top Fjerritslev Formation is onlapped by the Vedsted and Rødby formations, overlain by the Chalk Group. This major structural development and erosion at the Top Fjerritslev Formation probably took place at the 'Base Middle Jurassic unconformity' or 'Mid-Cimmerian Unconformity' described by Nielsen (2003) and which has resulted in major erosion and hiati in particular at structures and margins of the Danish Basin, including at the Ringkøbing-Fyn High nearby, south of the Stenlille-Havnsø area (Fig. 2). Further sequence stratigraphic, lithostratigraphic and biostratigraphic studies of the upper part of the Fjerritslev Formation is important to clarify how much is missing and/or condensed.

3.3. Depth and thickness maps

The depth-structure maps (Figs. 25–30) and thickness (isochore) maps (Figs. 31–34) are based on the regional seismic interpretation previously described with well ties in the Stenlille area, and offshore with ties to the Terne-1 well in Kattegat. The maps are all in two-way time and are depth converted in Mathiesen et al. (2020).

The horizons are gridded to maps by using the Petrel mapping facility ‘Make surface’. The horizons (TWT) are imported, fault polygons (if present) are imported, and the surfaces are gridded using: Grid increment (X, Y grid cell size): 500x500 m followed by 2x smoothing and with a search radius of 5 to reduce contour noise on the regional maps. The grid cell size and smoothing iterations control the contours: Larger grid cell sizes and more smoothing iterations result in coarser contours and preserves less of the original horizon surfaces.

The maps are based on interpretation of both the regional 2D seismic lines with large 2D line grid distances (3 – 5 km or more) and the Stenlille-97 3D survey with high-density data. It was decided to select a single grid-cell size of 500x500 m to justify the regional 2D lines in the regional maps in the present reporting. The data density is much higher in the 3D survey and a smaller grid cell size of e.g. 50x50 m is justified and used for maps within the 3D survey alone (see Vosgerau et al. 2020). The grid-cell size of 500x500 m is used in the regional maps to get some detailed contours over the Havnsø structure. Coarser grid cell sizes (km-scale) will significantly reduce the resolution of the structure. Smaller grid-cell sizes can on the other hand not be justified due to the large distances between seismic lines (data points).

The present mis-ties (see Section 2.1. Mis-tie analyses) between 2D sections and 3D data should be adjusted in follow-up work, but have not been changed in this project, as more work is required to solve the mis-ties. The maps are gridded from interpretation with the original database. Interpretation was only used from the 3D data in the 3D survey area to omit mis-fits from the 2D sections over the 3D area.

Gassum Formation

To improve the understanding of the structures and thickness of the Gassum Formation in the Havnsø structure, its base, top, internal sequence stratigraphic surfaces and faults are mapped. The Gassum Formation is a well-known, proven reservoir used for gas storage in the Stenlille area and is covered by sealing mudstones of the Fjerritslev Formation (see above). The Base and Top Gassum seismic horizons are defined on 2D and 3D seismic sections with well ties in the Stenlille structure (Figs. 10−13) and are correlated to the 2D seismic sections towards the Havnsø structure (Figs. 17 and 20). The poor data and mis-ties in the 2D surveys give uncertain correlation/interpretation (see Chapter 2. Data quality). This have influence on the maps and this should be considered when the maps are used.

The Base- and Top Gassum Formation Depth maps (TWT) in Figures 25 and 26 show shallowest parts (closures) over the Stenlille and Havnsø structures, separated by a saddle area approximately mid-way between the structures. The deepest parts are located west of the Havnsø structure. The Top Gassum Formation map (Fig. 26) shows that the top of the Stenlille and Havnsø are approximately at similar depth levels close to c. 1 second two-way time. Close examination of the digital map on workstation shows that the structure top points occur at c. 965 ms TWT (Stenlille structure) and c. 935 ms TWT (Havnsø structure), a difference of only c. 30 ms TWT. The lowermost closing contour (spill-point) in this map is at 1100 ms TWT, and the structurally closed area of the Havnsø structure is approximately twice as large as the closure area of the Stenlille structure. An area estimation of the Top Gassum closing contour of the Havnsø structure is performed on the depth-converted maps from Mathiesen et al. (2020). Some of the mainly NE − SW striking subtle faults (Fig. 24) at the Top Gassum Formation level are also shown. The only internal sequence stratigraphic surface that was possible to correlate to the Havnsø area is the Transgressive surface 5 (TS 5) in the Gassum Formation (Fig. 27). The TS 5 tops the lower sandstones of sequence 5 (Zone 5 reservoir sandstones in Fig. 12) and is at the same time an important regional surface marking the boundary to the more sandstone rich part of the lower Gassum Formation.

The thickness map of the Gassum Formation (Fig. 31) shows that the formation thickens considerably towards west and north-west into the Havnsø structure and increasingly west of the structure. However, the interpreted thickest westernmost parts is most likely related to problems with data at the map edges and may be erroneous. Similar local problems are observed on the other thickness maps (Figs. 32−34). The lower Gassum Fm below TS5 thickness map (Fig. 32) shows that the formation locally thins in the central parts of the Havnsø structure but thickens further west in the structure. The local thinning may be caused by initial movements of the underlying salt into a salt pillow that later developed and elevated the Havnsø structure (see Fig. 23).

Fjerritslev Formation and Base Chalk

The Maximum flooding surface 11 (MFS 11) in the Fjerritslev Formation (Fig. 28) and the Top Fjerritslev Formation (Fig. 29) also show shallow points and structural closures in the Stenlille and Havnsø structures. The lower part of the Fjerritslev Formation below MFS 11 (Fig. 34) is nearly of similar thickness in the top of the Havnsø structure as in the Stenlille structure but thickens farther westward. The Top Fjerritslev Formation is mapped to estimate the thickness of the Fjerritslev Formation down to the Top Gassum Formation (Fig. 33) and the maps also show a few of the NE − SW striking subtle faults in the Fjerritslev Formation (Fig. 24). The Fjerritslev Formation is thinning over the Havnsø structure (Figs. 24 and 33). This is probably due to the growth of the underlying salt pillow and erosion at the Top Fjerritslev Formation corresponding to the ‘Base Middle Jurassic unconformity’ during the mid-Cimmerian tectonic phase (Nielsen 2003; Fig. 2). The subtle faults from the Top Fjerritslev Formation and deeper into the Gassum Formation (Figs. 15, 16 and 24) may have been caused by the mid-Cimmerian tectonic phase and salt movements. Some of the faults also displace the lowermost Chalk Group. The faults have mostly minor vertical throws of c. 10−20 ms TWT, a few show larger displacement. The faults are mostly normal faults with a compressional to transpressional component and small flower structures are formed in places (Figs. 15 and 24). The Base Chalk Group Depth map (Fig. 30) also shows the top of the two structures and may be included in other work, e.g. if it is needed in depth conversion. Depth converted maps (see Mathiesen et al. 2020) will be used as basis for further conclusions on the depth and thicknesses of the formations and units.

4 Suggestions for supplementary investigations and research

This study shows that there are further investigations and research that can be carried out in order to improve data and the basis for interpretation and prediction of reservoir/seal sections as input for reservoir modelling in the Havnsø area. Here is listed several proposals to be considered:

- **A new 3D seismic survey covering the Havnsø structure**, with **2D tie line(s) to Stenlille wells**. It is critical to obtain a better defined structural closure and structure top. The detailed interpretation of sequences and seismic facies in the Stenlille-97 3D survey shows that interpretation of a new 3D survey will increase the understanding of sequences and faults, and sedimentary-related features such as channels, clinoforms etc. with the potential of significantly improving input to the reservoir models. Alternatively, a dense network of high-resolution 2D seismic data can be acquired. New 2D/3D data acquisition should cover both the offshore and onshore parts of the Havnsø structure.
- **A new direct 2D seismic line from the Stenlille-19 well to the Havnsø structure** is important for an improved well-tie to the Havnsø structure and to solve some of the mis-tie problems between the Stenlille and the Havnsø area.
- **A new mapping campaign with seismic interpretation based on new 3D/2D data** will improve the database and will be important for validation of the Havnsø structure and for accurate estimates of storage capacity. Such a study will improve interpretation of formation and sequence stratigraphic surfaces and units including thicknesses, improve definition of structural closures, faults, and of seismic facies and sedimentary related features and will feed into the establishment of reliable reservoir models and to the assessment of the storage capacity of CO_2 in the Havnsø structure.
- **Revision of time-depth relations and well-tops**. Evaluation and adjustments of time-depth relations in some of the Stenlille wells are needed to reduce or eliminate mis-fit between well-tops/logs and seismic data. In addition, stratigraphic/depth positions of well-tops should be reevaluated.
- **Reprocessing of existing 2D lines** that define the Havnsø structure may be performed, as reprocessing has shown important improvements of the data quality and has strengthened the seismic interpretation.
- **Re-scanning** and mis-tie correction of the old scanned seismic lines to improve the seismic database.
- **Adjustment mis-tie of 2D and 2D/3D data**. A study to sort out how to minimize the mis-ties on the existing 2D/3D seismic data. This will be most optimal if new acquired 2D seismic line(s) between the Stenlille and Havnsø structures is used and after re-scanning of the old, scanned data.

A new 3D seismic survey in the Havnsø area is of highest priority as this will improve the seismic database for interpretation of the Gassum Formation reservoir sections and overlying seal sections of the Fjerritslev Formation. New 3D data will, based on assessment of the Stenlille-97 3D survey, give a much better vertical and horizontal data resolution and an improved interpretation of details of mainly the reservoir sections. This will provide new input for assessment of the CO_2 storage capacity in the Havnsø structure, which is mandatory as input to the reservoir modelling and simulations.

References

Bredesen, K. 2020: Capture, Storage and Use of CO_2 (CCUS): Quantitative seismic interpretation (rock physics models, seismic inversion, AVO and attribute analysis) (Part of work package 5 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2020/52, 9 pp.

Hamberg, L. & Nielsen, L.H. 2000: Shingled, sharp-based shoreface sandstones: depositional response to stepwise forced regression in a shallow basin, Upper Triassic Gassum Formation, Denmark. In: Hunt D. & Gawthorpe R.L. (eds.): Sedimentary Responses to Forced Regressions, Geological Society, London, Special Publications 172, 69–89.

Hovikoski, J. & Pedersen, G.K. 2020: Capture, Storage and Use of CO_2 (CCUS): Sedimentological description of Gassum and Fjerritslev Formations from cores in the Stenlille area, with interpretations of depositional environments (Part of work package 6 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2020/42, 61 pp.

Kristensen, L. 2020: CCUS project. Capture, Storage and Use of CO_2 (CCUS): Reservoir data – Stenlille area (Part of work package 6 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2020/28, 55 pp.

Lindström, S. 2020: Capture, Storage and Use of CO_2 (CCUS): Palynology of the Gassum and lowermost Fjerritslev formations in the Stenlille area: biostratigraphic and palaeoenvironmental implications (Part of work package 6 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2020/36, 43 pp.

Mathiesen, A., Laghari, S. & Rasmussen, R. 2020: Capture, Storage and Use of CO_2 (CCUS): Depth conversion of seal and reservoir maps from the Havnsø and Hanstholm areas (Part of work package 5 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2020/35, 43 pp. + 2 App.

Nielsen, L.H. 2003: Late Triassic – Jurassic development of the Danish Basin and the Fennoscandian Border Zone, southern Scandinavia. In: Ineson, I. & Surlyk, F. (eds.): The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin 1, 459–526.

Nielsen, L.H., Larsen, F. & Frandsen, N. 1989: Upper Triassic – Lower Jurassic tidal deposits of the Gassum Formation on Sjælland, Denmark. Geological Survey of Denmark, DGU Series A, v. 23, 30 pp.

Vosgerau, H., Gregersen, U. & Laghari, S. 2020: Capture, Storage and Use of CO_2 (CCUS): Seismic interpretation of existing 3D seismic data around the Stenlille structure within the framework of sequence stratigraphy and with focus on the Gassum Formation (Part of work package 6 in the CCUS project). Danmarks og Grønlands Geologiske Undersøgelse Rapport 2020/34, 53 pp.

Figures

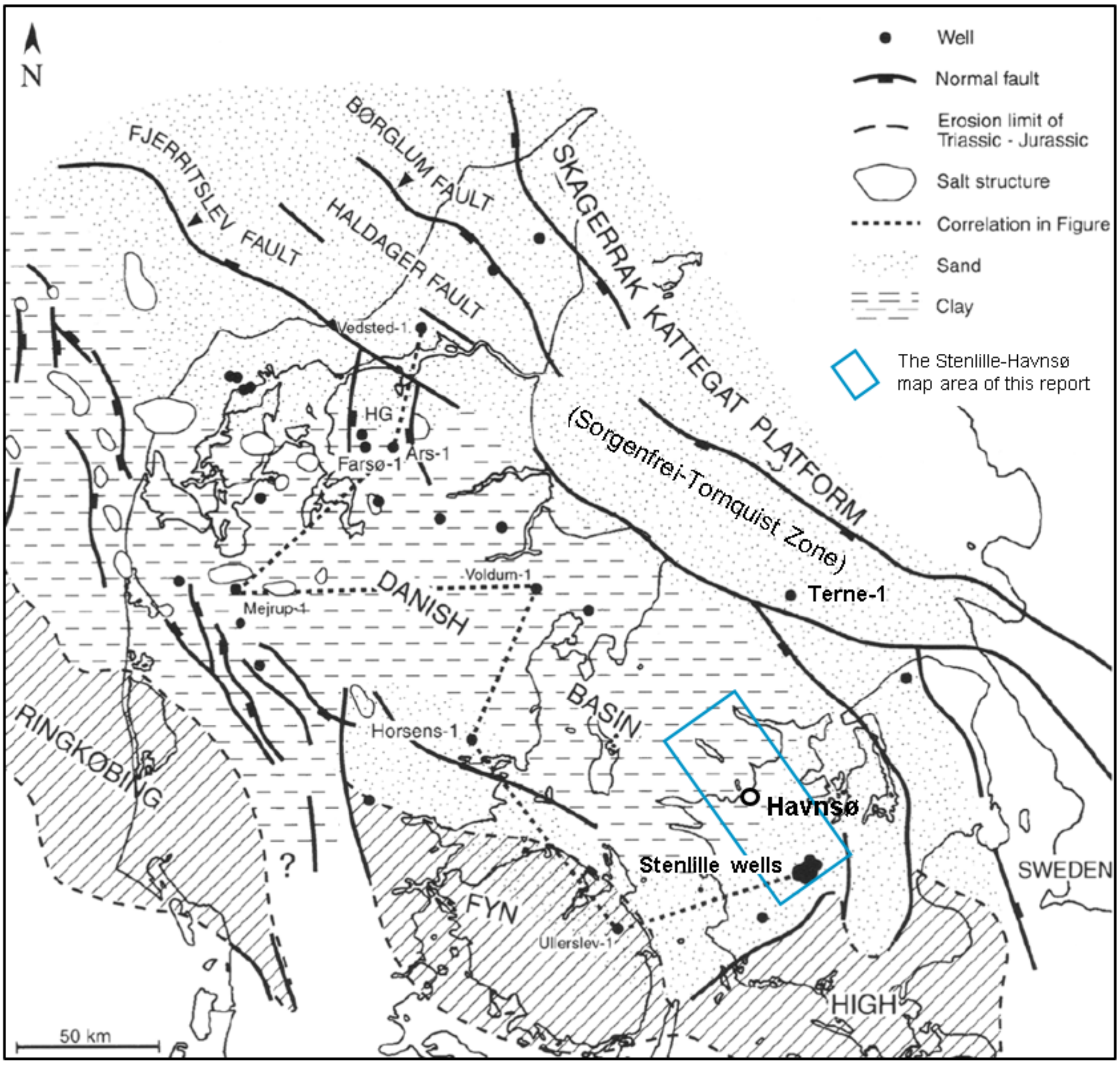


Fig. 1. Regional palaeogeographic map from Hamberg & Nielsen (2000) with the Stenlille to Havnsø area (Havnsø is marked) of the present reporting in the blue frame and positions of wells. The study area is located in the eastern part of the Danish Basin, between the Ringkøbing−Fyn High and the Sorgenfrei-Tornquist Zone. The map shows a palaeogeographic reconstruction of the Upper Triassic during which the sediments from the upper parts of the Gassum Formation is possibly in an overall more claystone (distal) position of the Havnsø area compared to the more sand dominated (more nearshore) Stenlille area.

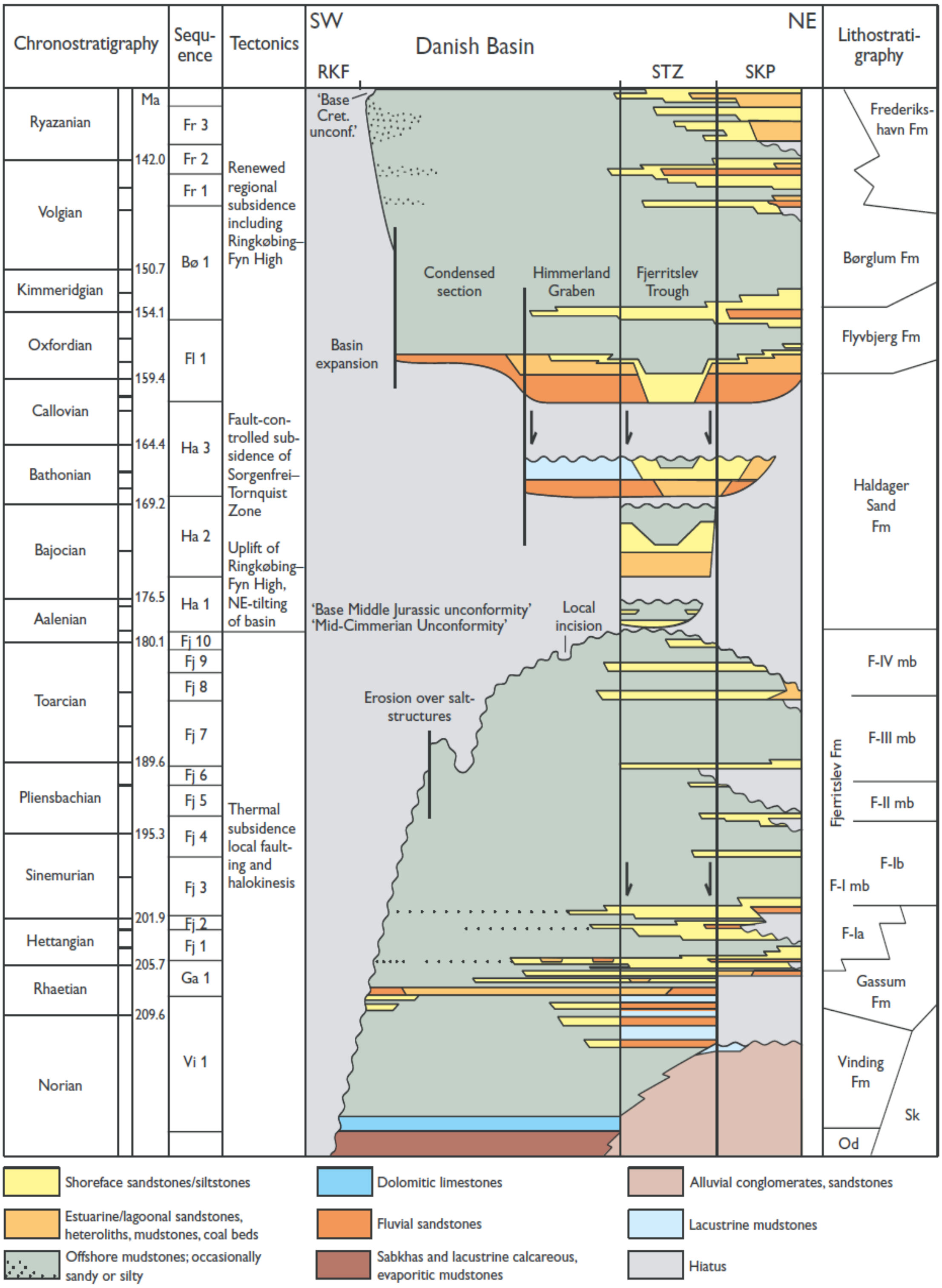


Fig. 2. Regional stratigraphy from Nielsen (2003), showing the Gassum and Fjerritslev formations and tectonics of the Danish Basin. The Stenlille area is located further east of this profile, but is north of the Ringkøbing-Fyn High (RFH) and south of the Sorgenfrei-Tornquist Zone (STZ).

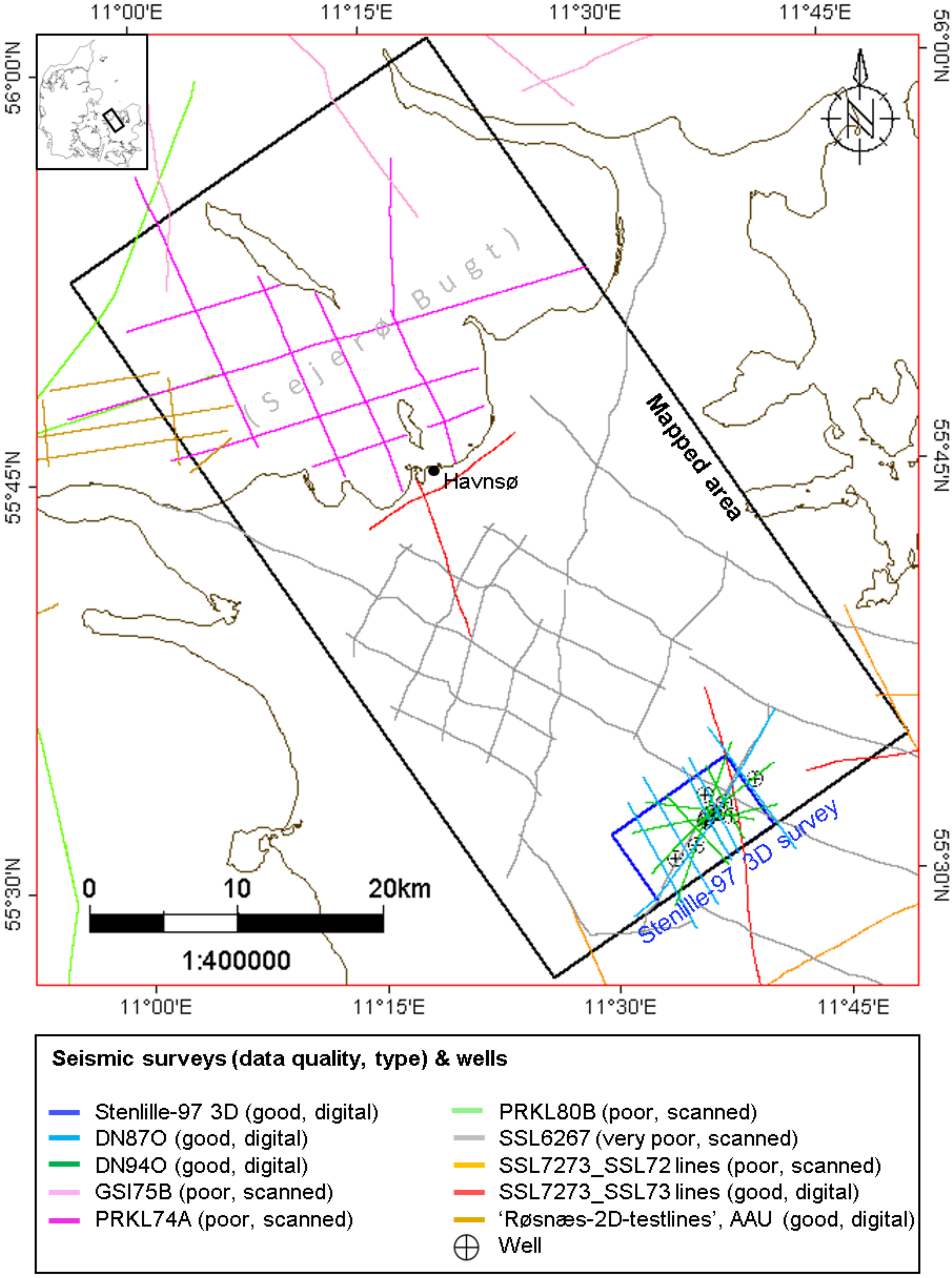


Fig. 3A. Database map with Stenlille wells, Stenlille-97 3D and 2D seismic surveys. The data quality of the 2D data is mostly poor on the scanned sections. Only in the Stenlille area a good database exists with the 3D seismic data and wells (see Fig. 3B).

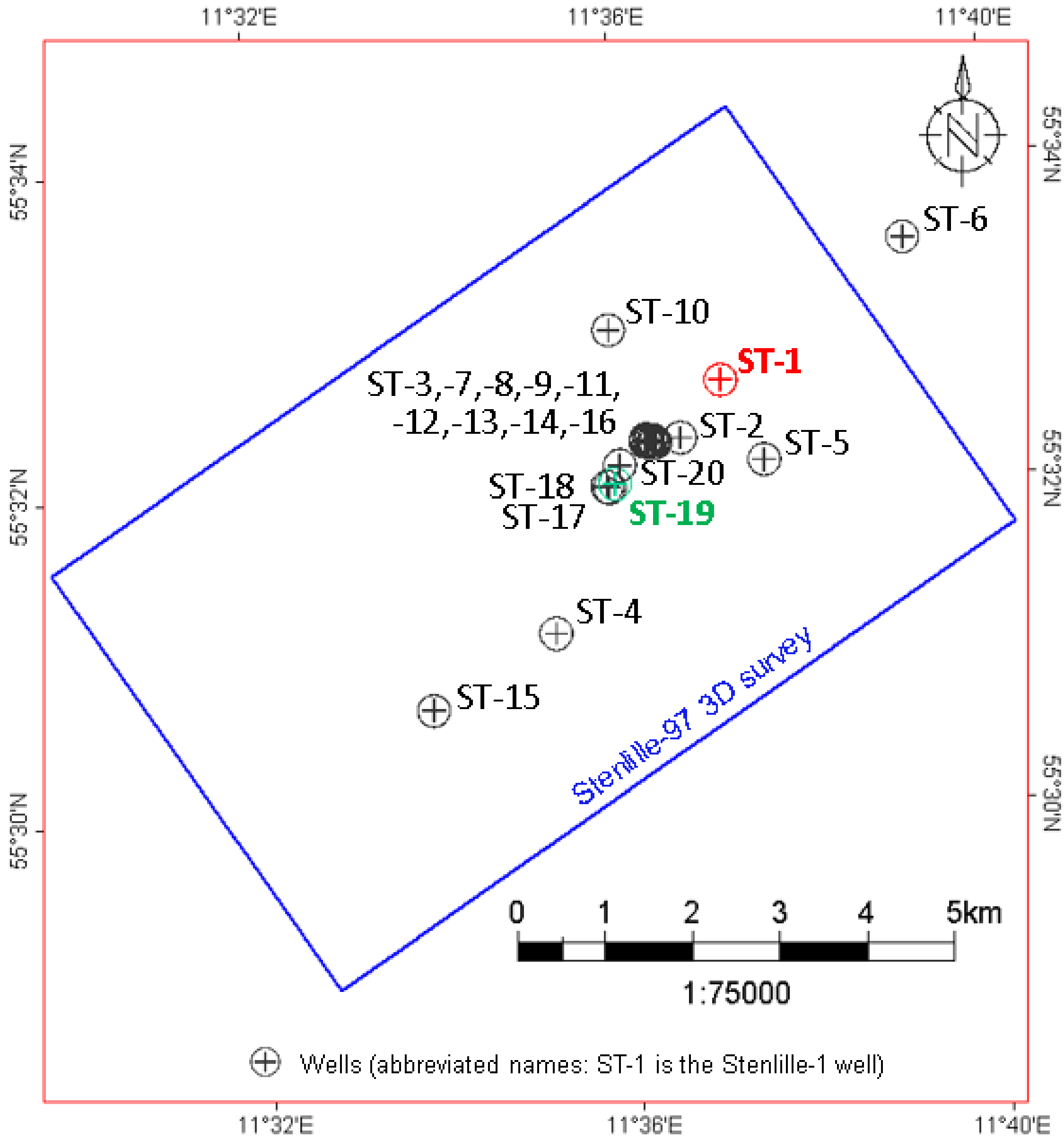


Fig. 3B. Database (Fig. 3A) zoomed to the Stenlille 3D survey and the Stenlille wells. The names of the Stenlille wells are abbreviated, e.g. is ST-1 Stenlille-1 well. The two key wells used mostly are marked with color: ST-1 in red and ST-19 in green.

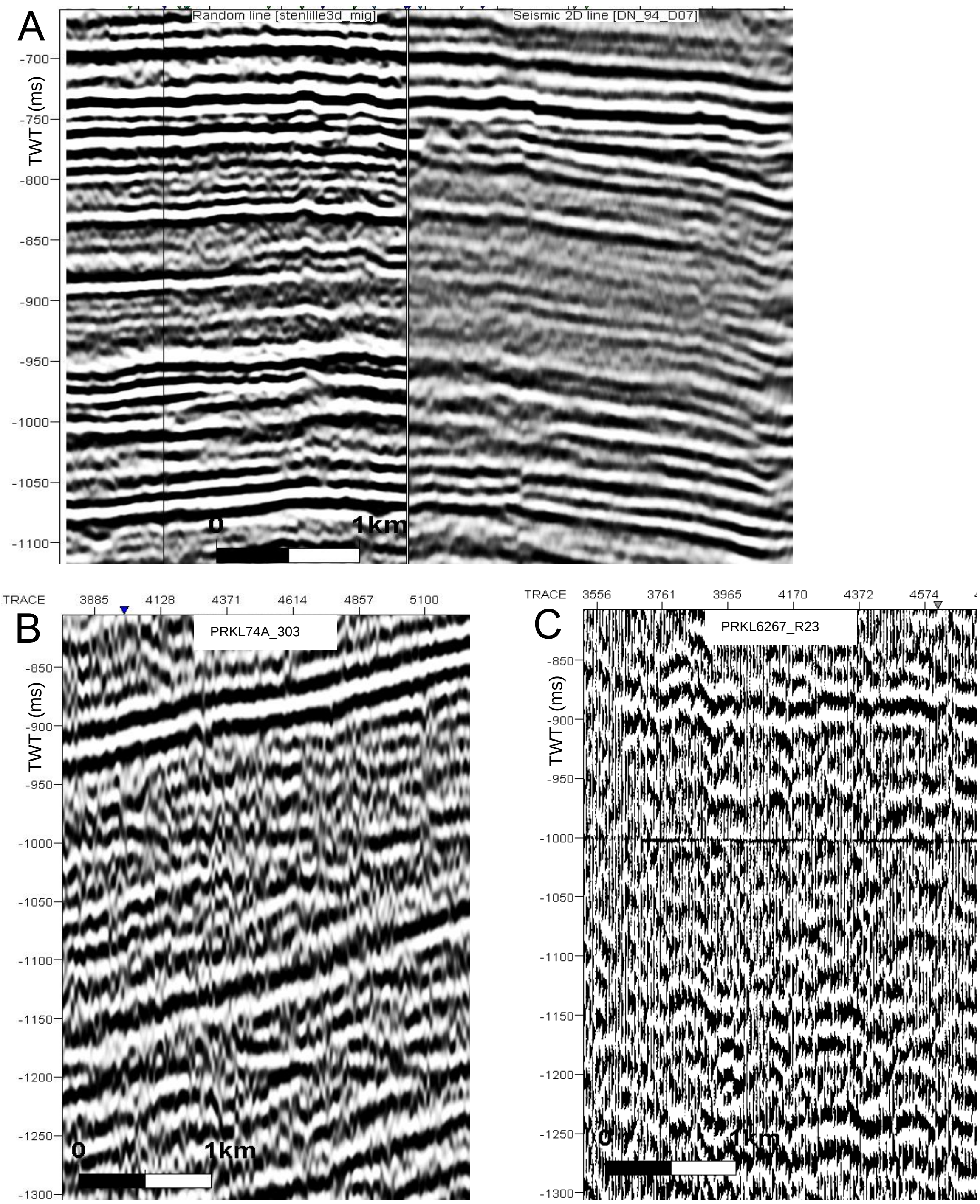


Fig. 4. Examples of seismic data with different data quality in the interval from the Gassum Fm to near Base Chalk (line names in the top): (A) Good data quality of digital seismic data from the Stenlille area with 3D data (left) and 2D data (right), shifted15 ms up to fit 3D data. (B) Poor data quality of scanned 2D seismic data from the Sejerø Bugt, the key-survey over the northern offshore part of the Havnsø structure. (C) Very poor data quality of scanned 2D seismic data from the key onshore survey at the Havnsø structure. This is also the key tie survey to the Stenlille area.

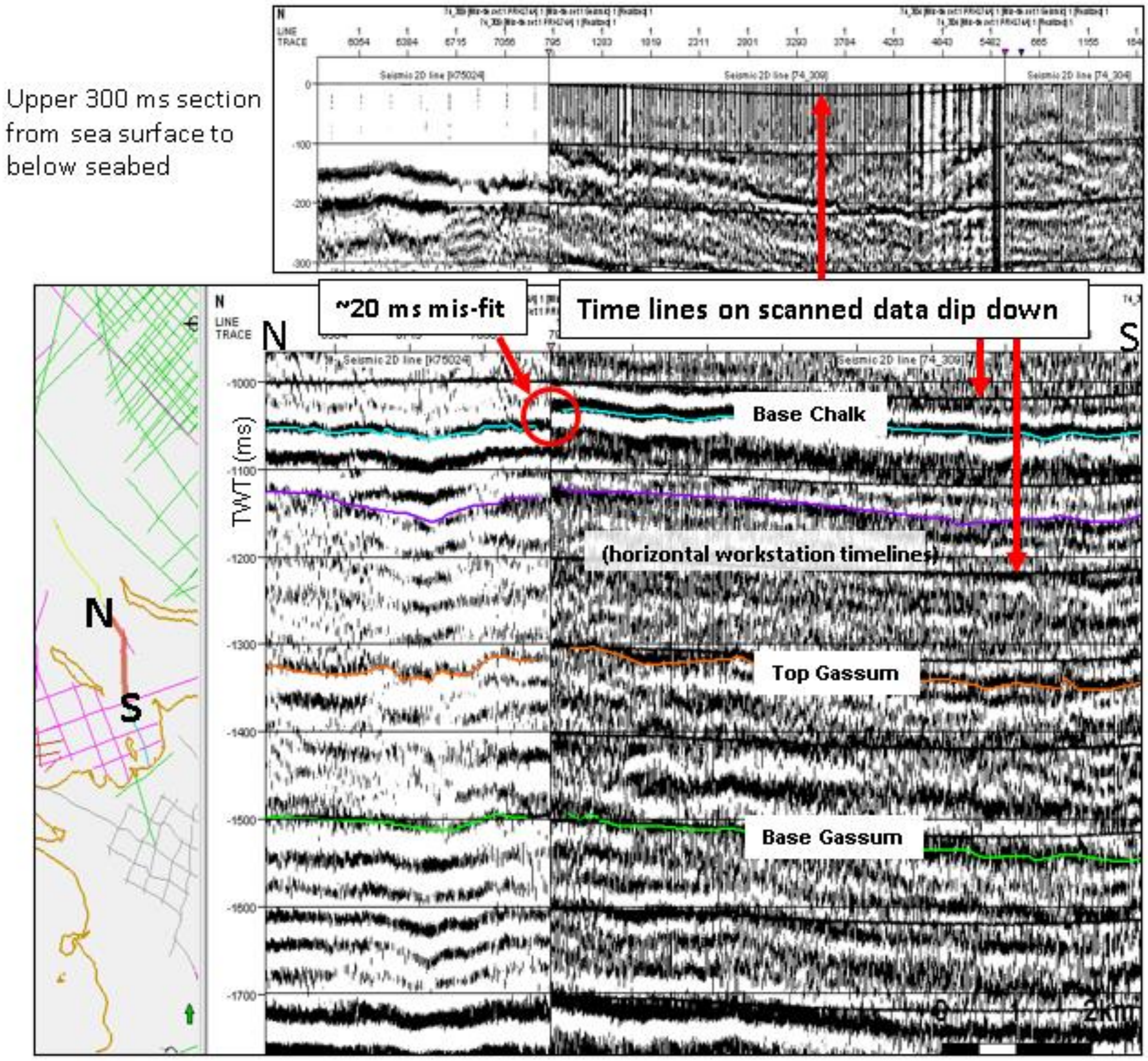


Fig. 5. Mis-ties of data was found during visual screening and in analyses via Petrel. The figure shows a composite profile with seismic sections K75024 of survey GSI75B (left) and 74_309 of survey PRKL74A (right) in the northern Sejerø Bugt. These scanned seismic sections are of poor quality, but they show a high amplitude reflection, which is interpreted as the Base Chalk horizon (blue). There is apparently a mis-tie between the two lines shown by a c. 20 ms mis-fit of reflections at the Base Chalk and less on deeper levels. The thin timeline 1000 ms in workstation display matches the scanned timeline in line K75024 (left). Time lines on the scanned section 74_309 (right) match at the tie point with the left section K75024, both at 0 ms and deeper (e.g. 1000 ms), but the time lines of the scanned sections dip down towards right (at red arrows) and mis-match the thin workstation time lines. Seismic sections from both the PRKL74A and GSI75B apparently dip compared to the workstation timelines. The position in time of seismic sections from these two surveys are presently uncertain. The sections should be checked from reporting and scanned again. There are only poor seismic data for ties to the nearest offshore wells as Terne-1 (see below). Thus, mis-tie correction of the survey lines is difficult and omitted here, and the data mis-tie uncertainty is c. 10−20 ms at the Top Fjerritslev and Top Gassum levels.

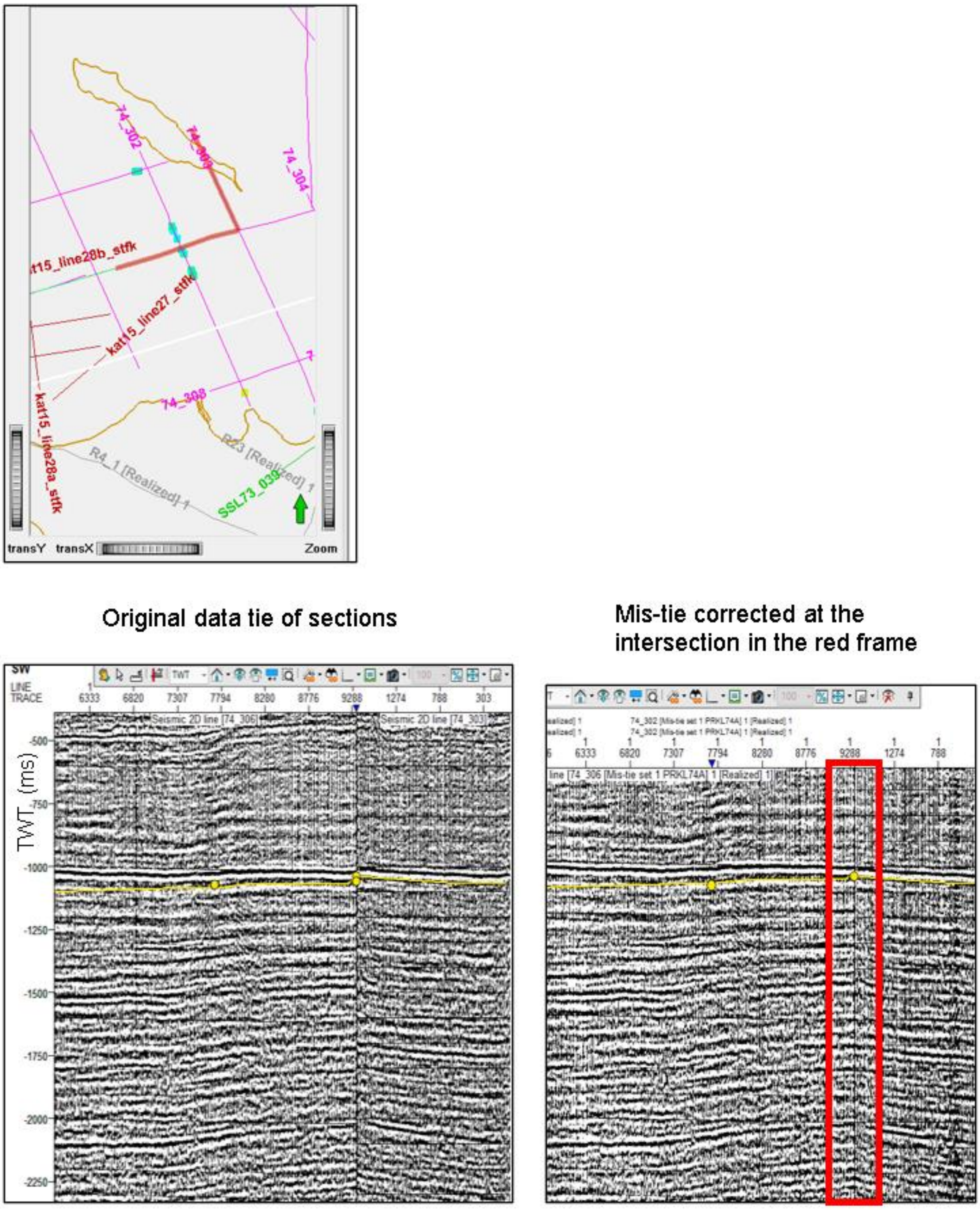


Fig. 6. Mis-ties of data were found during screening and in analyses via Petrel. Analyses were performed in the Sejerø Bugt as this example shows from the 2D survey PRKL74A. Additional figures from the Petrel mis-tie analyses are shown in Figures 7 and 8, and in Appendix 1.

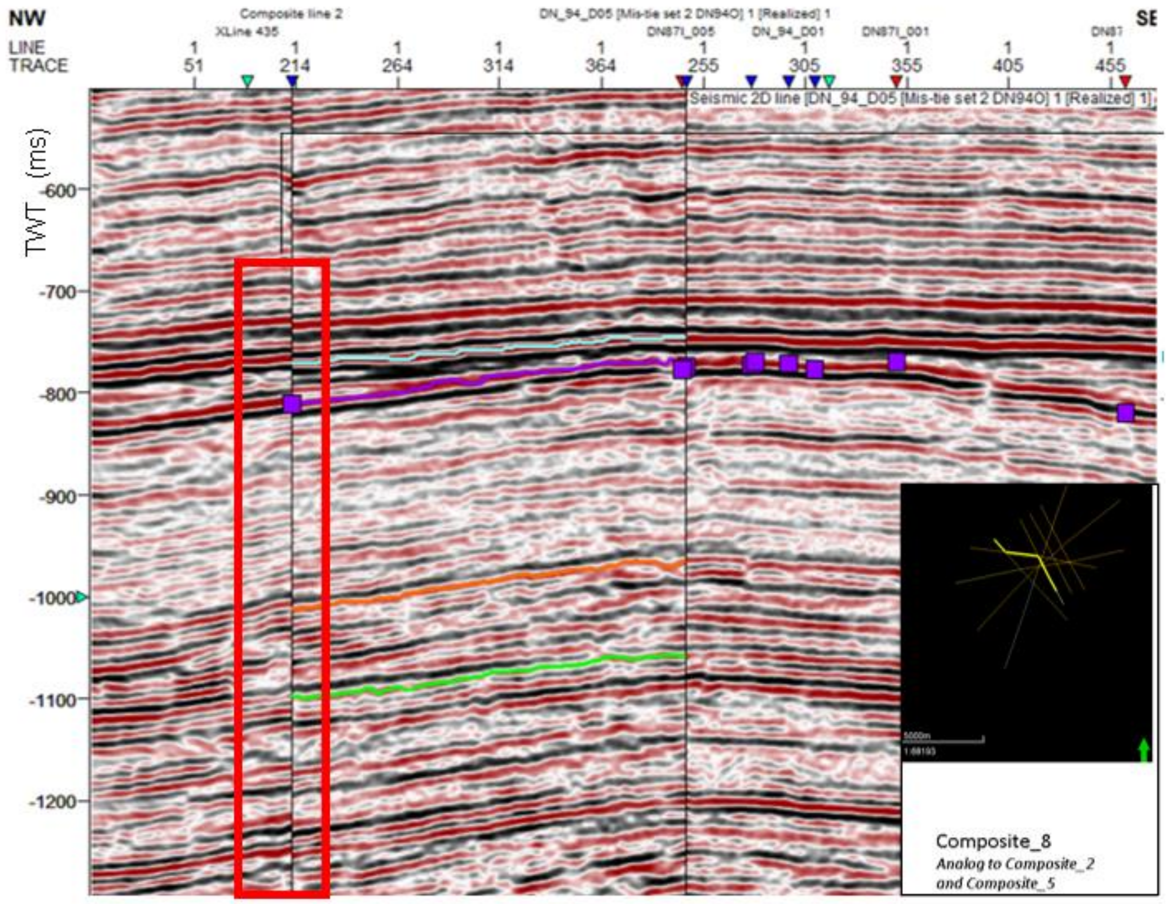


Fig. 7. The figure shows a composite section over the Stenlille 3D area with lines of the same survey (DN94O). The survey (including these lines) have been corrected with a constant shift in Petrel, but this section shows that there are still mis-ties at some lines of the same survey. The mis-tie between lines DN94_D03 and DN94_D04 in the red frame is almost one cycle, whereas the seismic sections fit in the other line-intersection. Please note the clear onlaps at c. 800 ms TWT on the red reflector, which is the regionally correlated Top Fjerritslev (purple horizon). This reflection is ½ cycle above the black reflector (white on black-grey-white color table), which was decided to be picked as the clearest Top Fjerritslev reflection (e.g. purple point right hand, at c. Trace 455) in the 3D survey (see also Fig. 10).

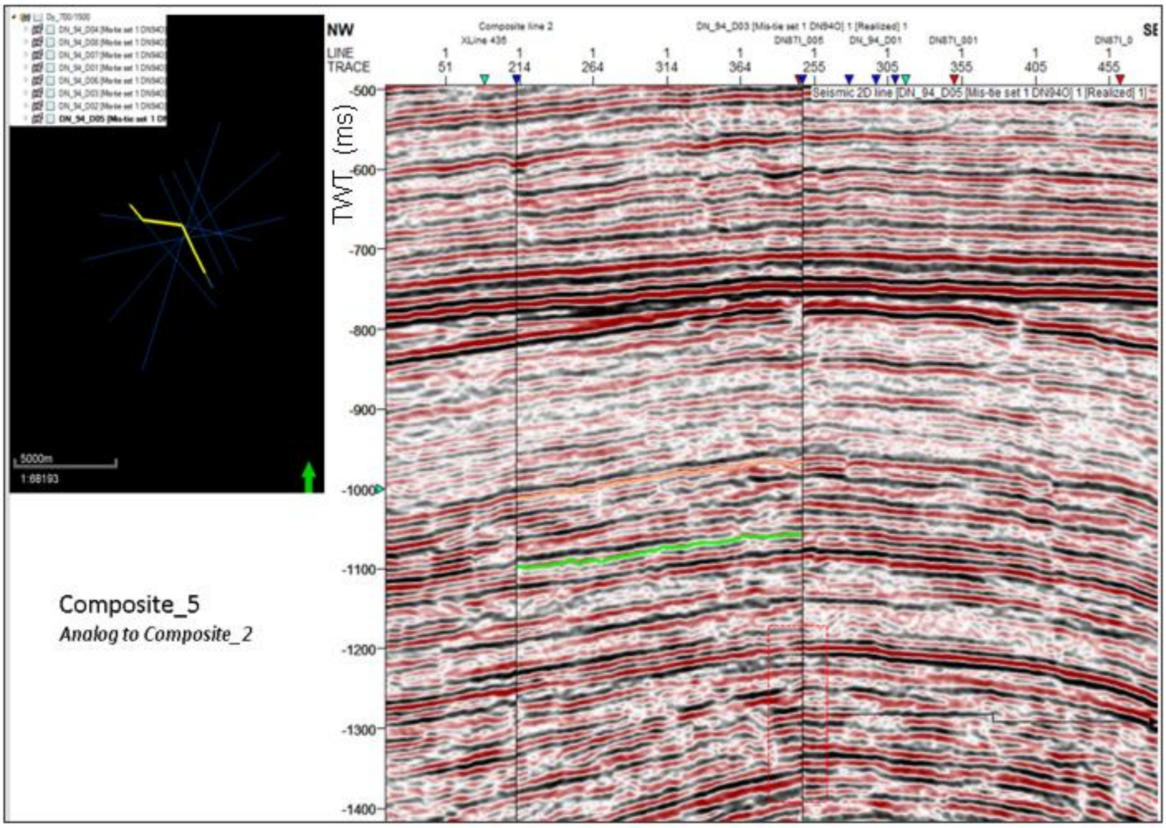


Fig. 8. The figure shows a composite section over the Stenlille 3D area with lines of the same survey (DN94O). The lines have been corrected with variable (dynamic) shift in Petrel in a time window down to 1500 ms TWT. This ”data-stretch” seems to give a more complete match of the seismic lines than if a constant shift is used. However, as this will ”stretch” the data, this is not used here, but it demonstrates a challenge for mis-ties to be corrected. Please note the clear onlaps at c. 800 ms TWT on the red reflector, which is the regionally correlated Top Fjerritslev, which is ½ cycle above the black reflector (white on black-grey-white color table), which is picked as the clearest Top Fjerritslev reflection in the 3D survey (Fig. 10).

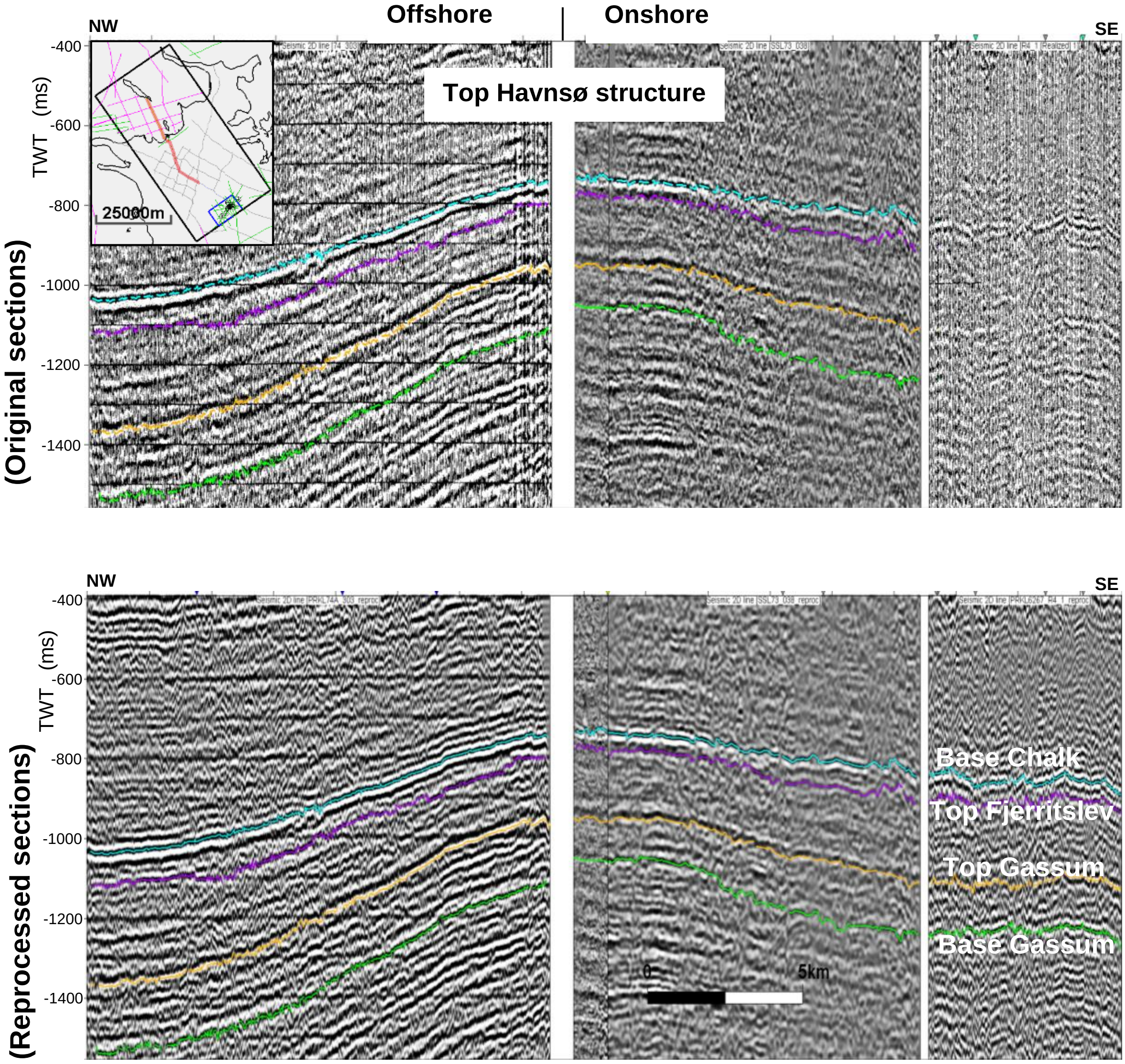


Fig. 9. The three seismic sections: PRKL74A_303 (left), SSL73_038 and PRKL6267_R4_1 (right) have been reprocessed. The upper composite profile shows the original seismic sections and the lower profile shows the reprocessed sections. The reprocessing resulted in improved quality with respect to continuity and resolution and allows correlation of seismic horizons. However, the data is still not good enough to allow detailed interpretation of seismic facies/features from the Stenlille area and towards the Havnsø area. The profile location with the sections is shown in the small map as bold red colored lines. Appendix 2 includes the three lines without interpretation.

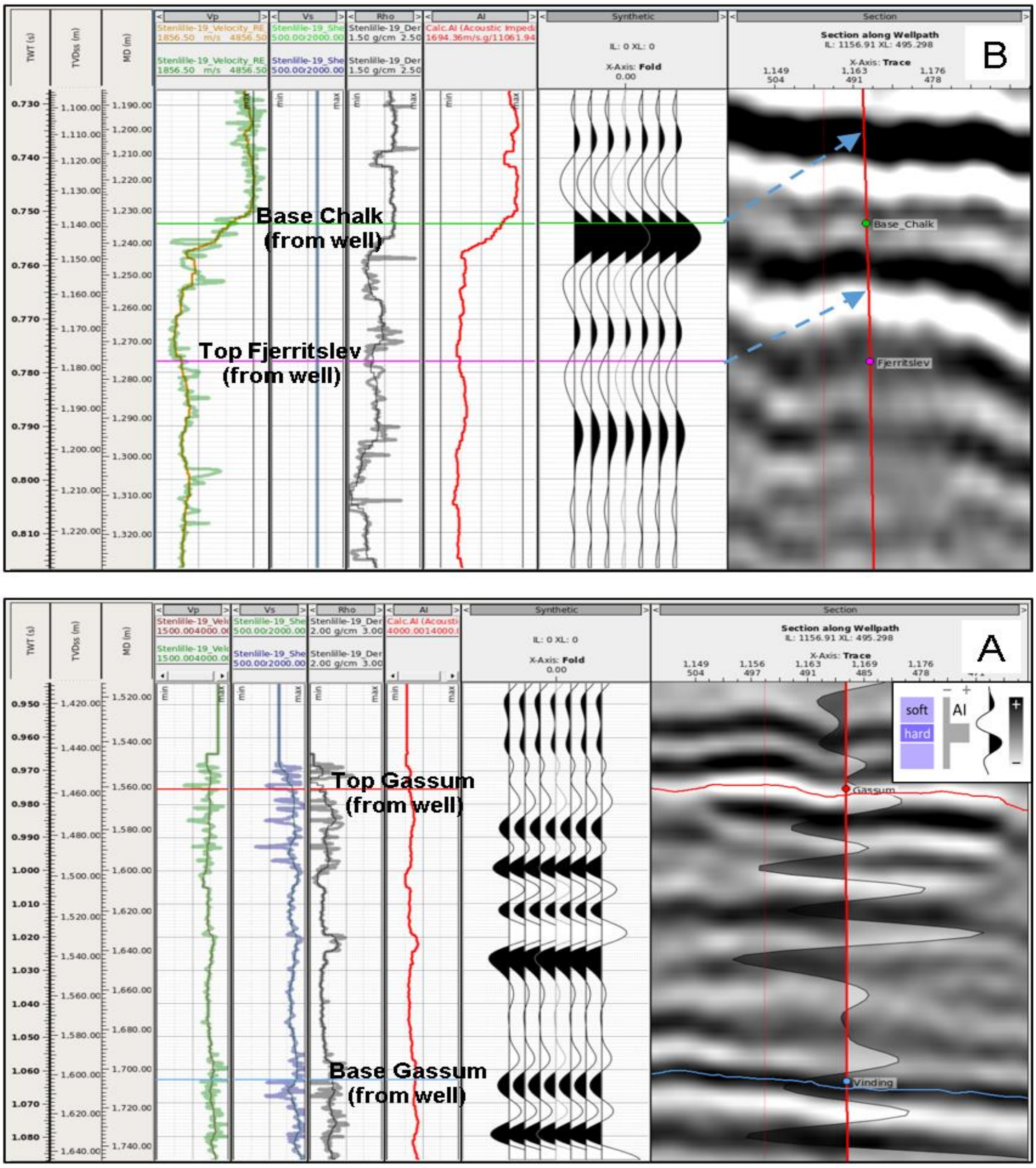


Fig. 10. The Stenlille-19 well with (from left to right) Vp, Vs, Rho, Acoustic impedance (AI), a synthetic seismogram and a seismic section from the 3D survey with well-tops. (A) The synthetic seismogram for the Gassum Formation interval fits at a black peak for Base Gassum and near a white trough for the Top Gassum. The small insert figure shows the expected Acoustic impedance at the interface from soft over harder rocks, e.g. at Top Gassum Fm. (B) Positions of Top Fjerritslev and Base Chalk in the well and synthetic seismogram should compared to the seismic section be interpreted up above well-tops to fit the seismic section, shown with blue arrows. The Top Fjerritslev then comes close to the zero-crossing. The Base Chalk is interpreted in the black, strong amplitude peak.

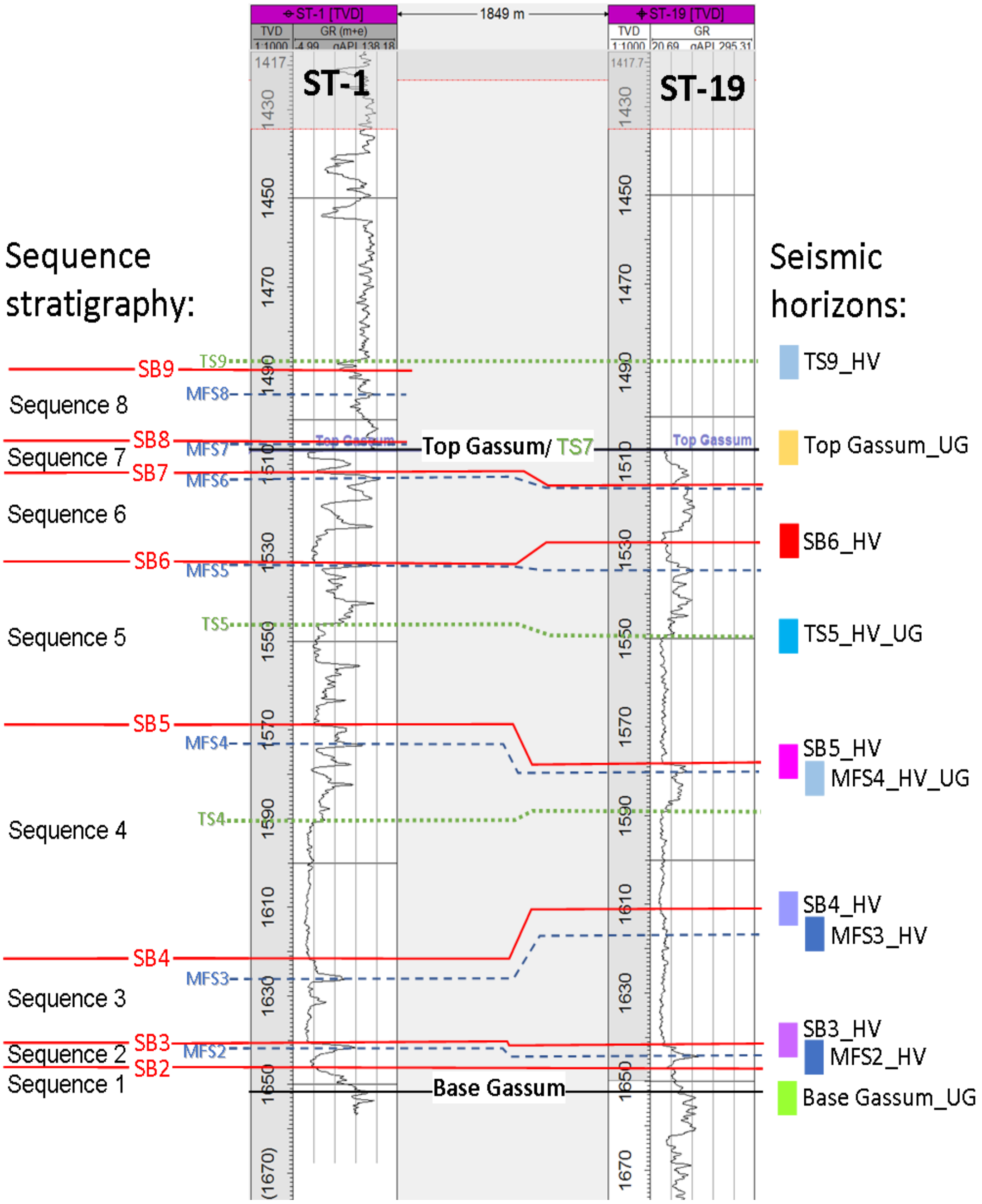


Fig. 11. Stenlille-1 (ST-1) and Stenlille-19 (ST-19) wells with gamma log (GR), and well-tied sequence stratigraphic boundaries and interpreted seismic stratigraphic horizons from Vosgerau et al. (2020).

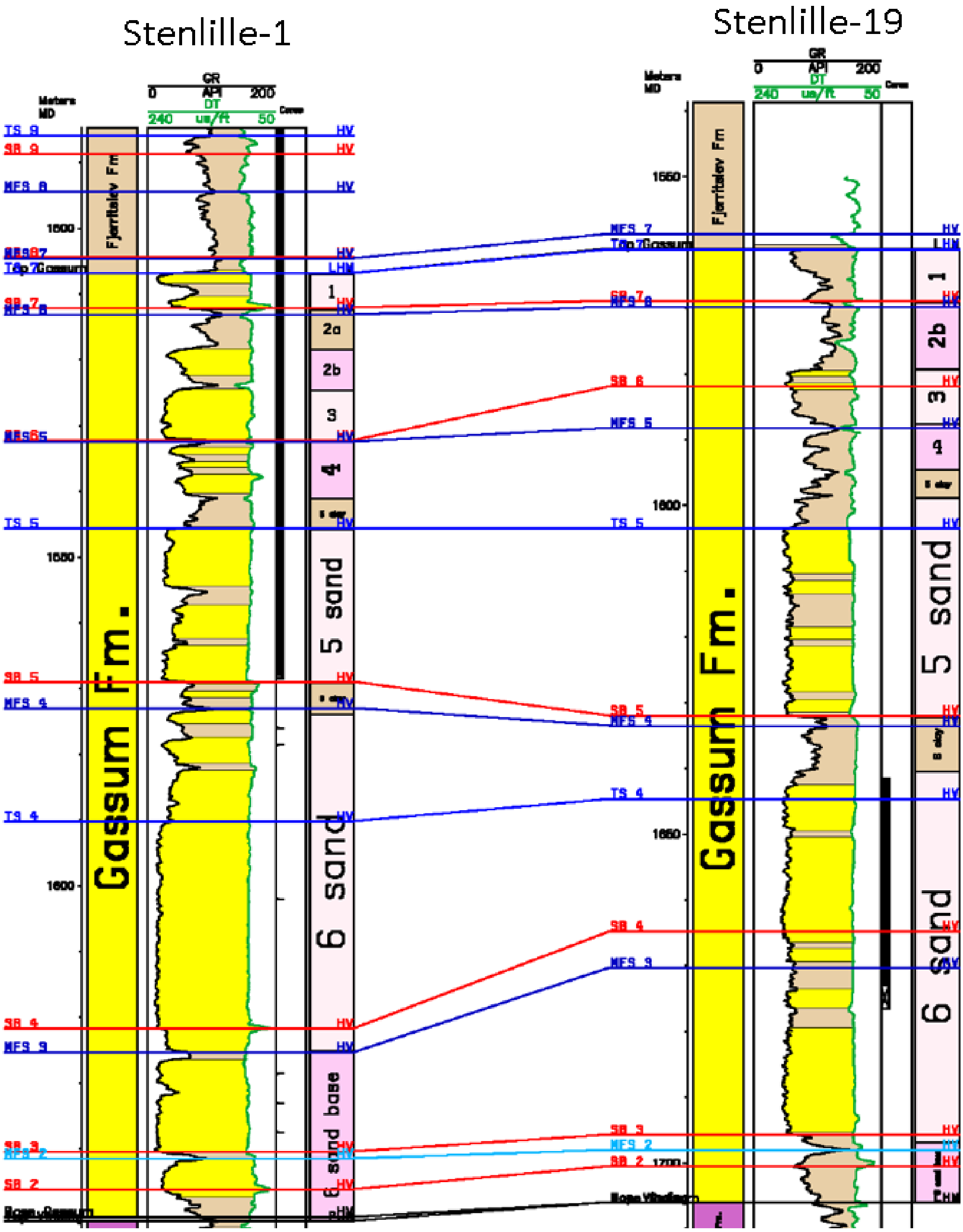


Fig. 12. Stenlille-1 and Stenlille-19 wells with gamma log (GR) and sonic log (DT), and well-tied sequence stratigraphic surfaces and formations from Vosgerau et al. (2020). These wells are also used in Figure 13. Yellow is sandstone dominated and brown is mudstone/claystone dominated. In addition, reservoir/seal zones (1−6) are also shown (see Kristensen 2020). Thick, black vertical lines indicate cored sections.

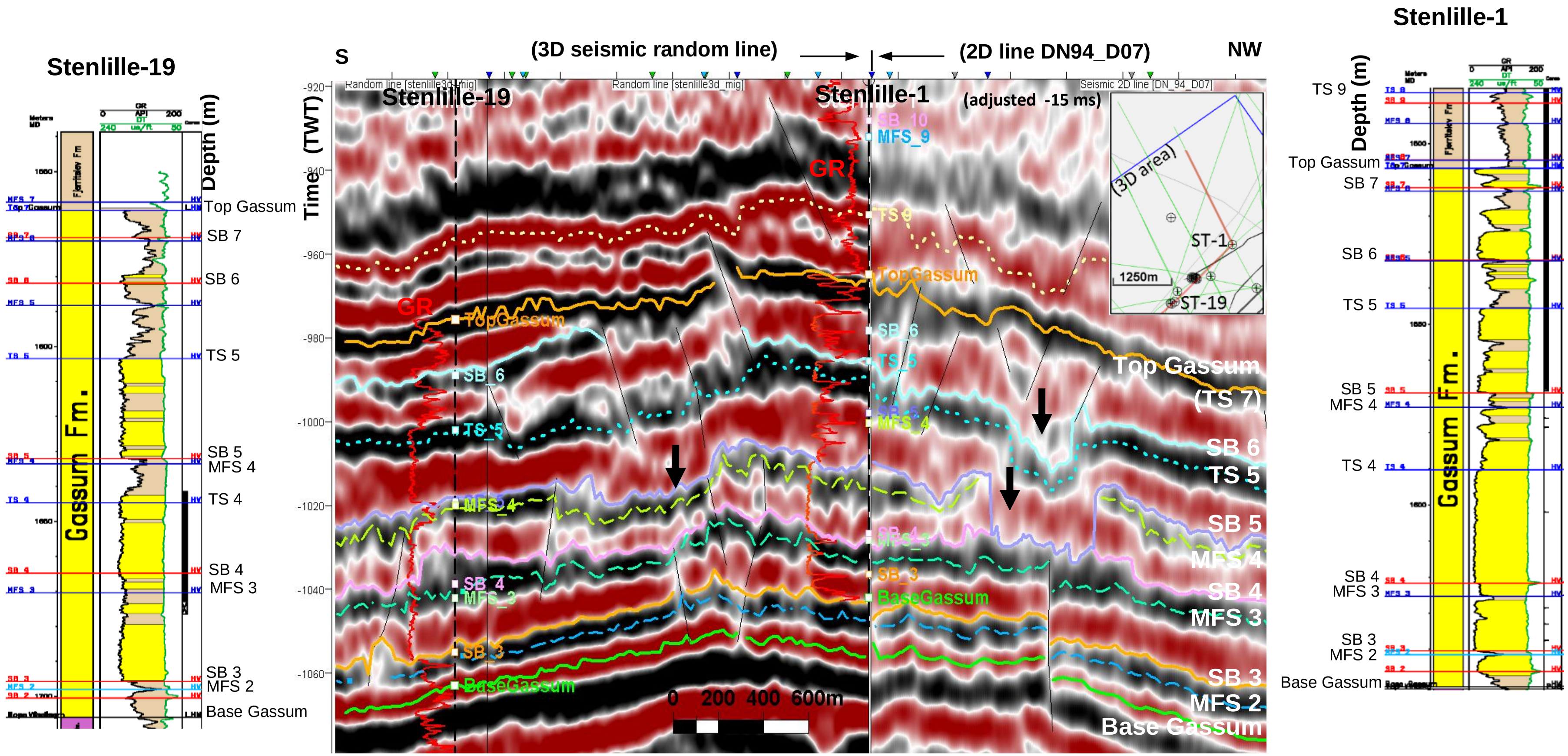


Fig. 13. Seismic-well correlation on a 3D seismic random line and 2D seismic line DN94_D07 (adjusted -15 ms) with well Stenlille-1 (ST-1) and Stenlille-19 (ST-19) with sequence stratigraphic horizons in the Gassum Fm, gamma ray logs (GR) and well-tops displayed. Base Gassum and Top Gassum are strong, continous reflections of opposite phase. Note the erosive and thickening troughs/channels (black arrows) at the SB5 and SB6 and the many minor faults. The GR log trace in the Gassum Fm in ST-1 (incl. Base Gassum well-top) seems to be too shallow in relation to the 3D seismic correlation, possibly due to time-depth relations, that may be adjusted after a new revision. The 2D line (right of 3D/ST-1 well) is here adjusted -15 ms to fit the 3D seismic data. The sequence stratigraphic boundaries are defined and detailed interpreted on the 3D seismic data by Vosgerau et al. (2020).

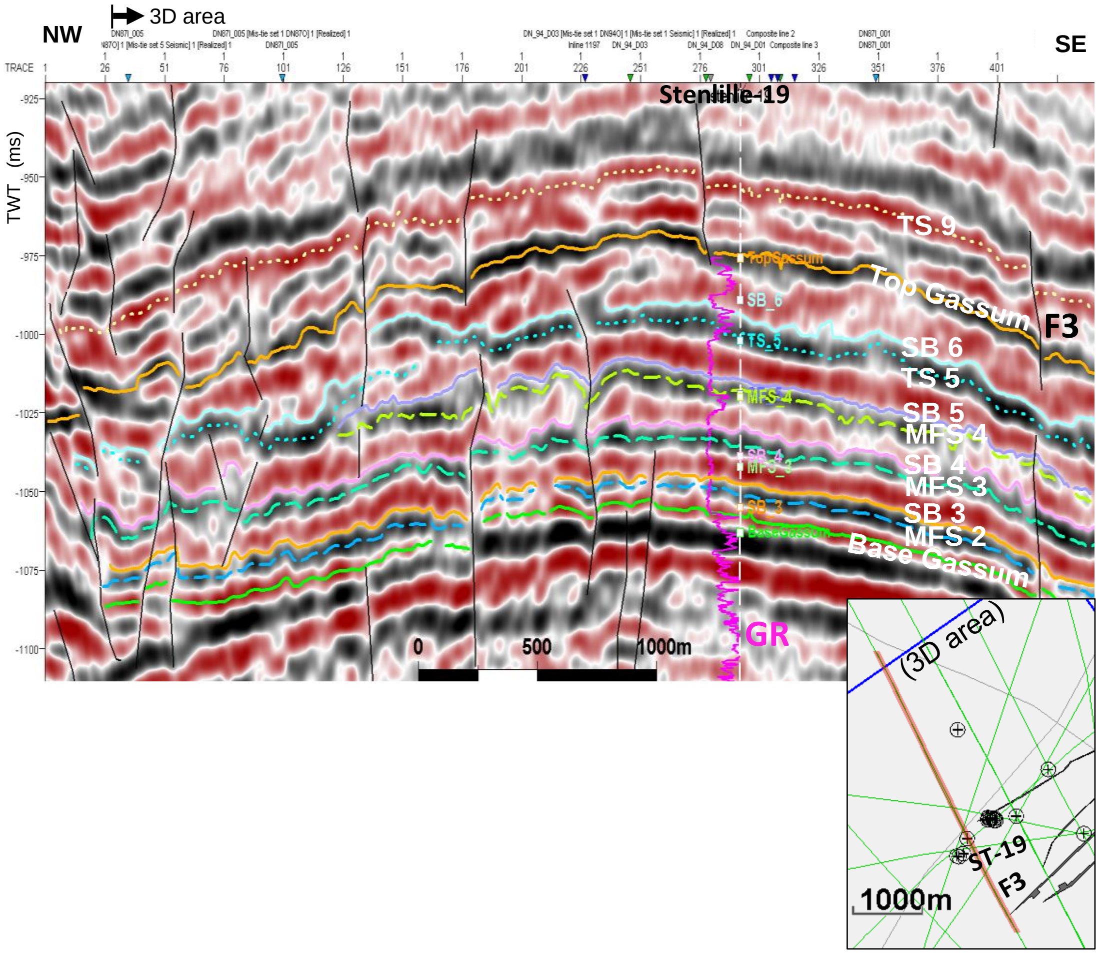


Fig. 14. 2D seismic seismic section DN94_D05 (adjusted -15 ms) NW-SE across the Stenlille structure with the Stenlille-19 well, showing the faulted horizon ties through a fault zone at the NW boundary of the 3D survey area.

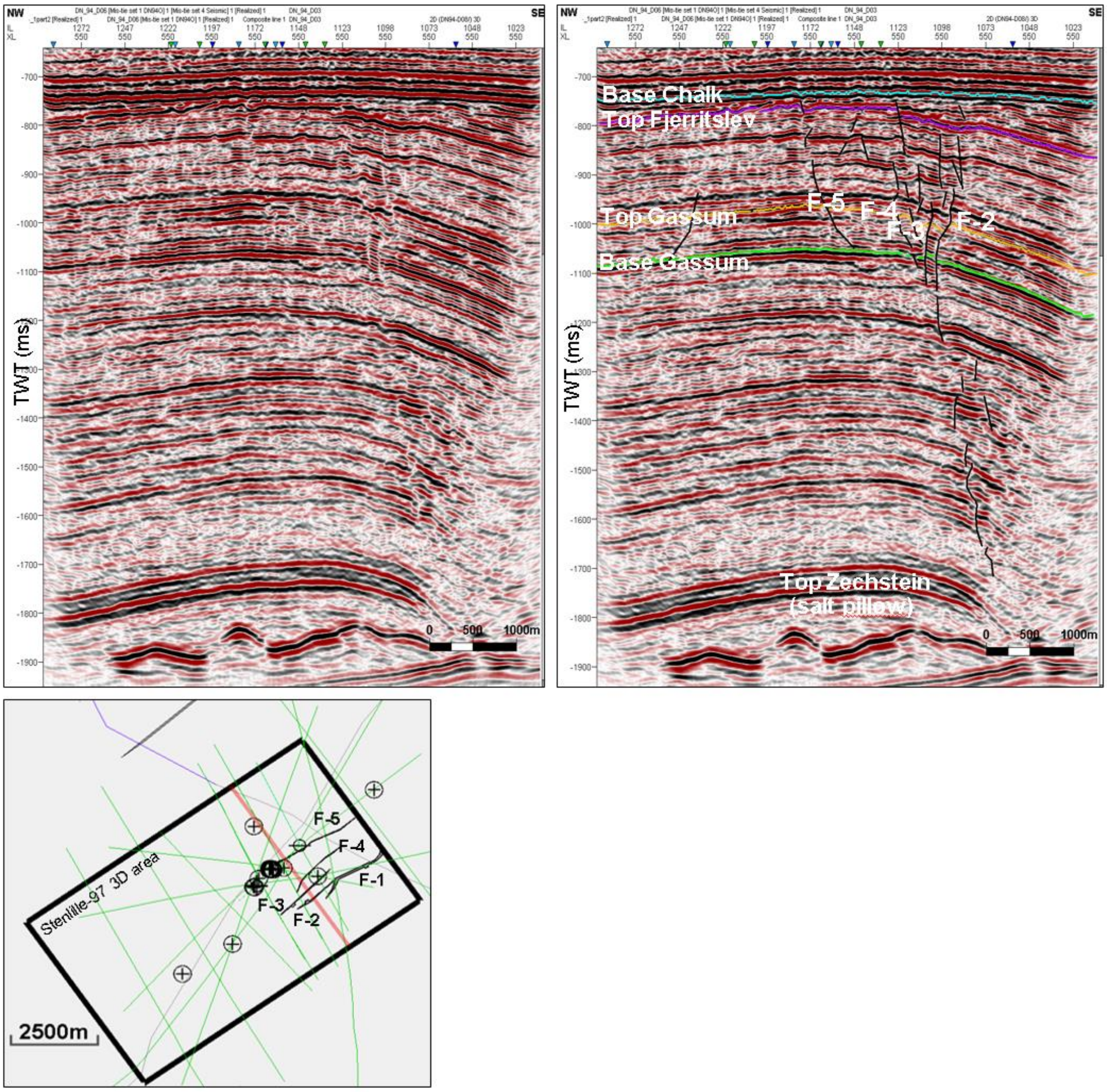


Fig. 15. X-line 550 (NW to SE) of the Stenlille-97 3D survey from NW to SE, showing the interpreted horizons: Base Gassum (green), Top Gassum (orange), Top Fjerritslev (purple), Base Chalk (blue) and faults. The map shows the position of the seismic line and faults (F-1 to F-5) at the Top Gassum level. The interpreted section illustrates that the SE part of the survey area has been faulted at the Top Gassum to the Top Fjerritslev level and that the faults mostly disappear at and above the Base Chalk level. Faults F-2 to F-4 constitute the boundaries of the central part of the flower structure, which seems to be rooted at the SE flank of the underlying salt pillow below the Top Zechstein. F-5 forms an outer rim of this flower structure. Throws at the structures at Top Gassum and Fjerritslev Fm, both in the Stenlille and in the Havnsø area are mostly between c. 10-20 ms TWT (c. 10−30 m). The salt pillow has raised the whole succession from Top Zechstein to the Top Fjerritslev Fm. This level likely represents the base mid-Jurassic unconformity (mid-Cimmerian unconformity), overlain by regional onlap from a thin succession here including the Vedsted Fm (Stenlille-1). The formation of the salt pillow and the associated flower structure and thus the Stenlille structure may have occurred mainly near the Top Fjerritslev Fm level and before the Chalk Group was deposited over/across the top of the structure.

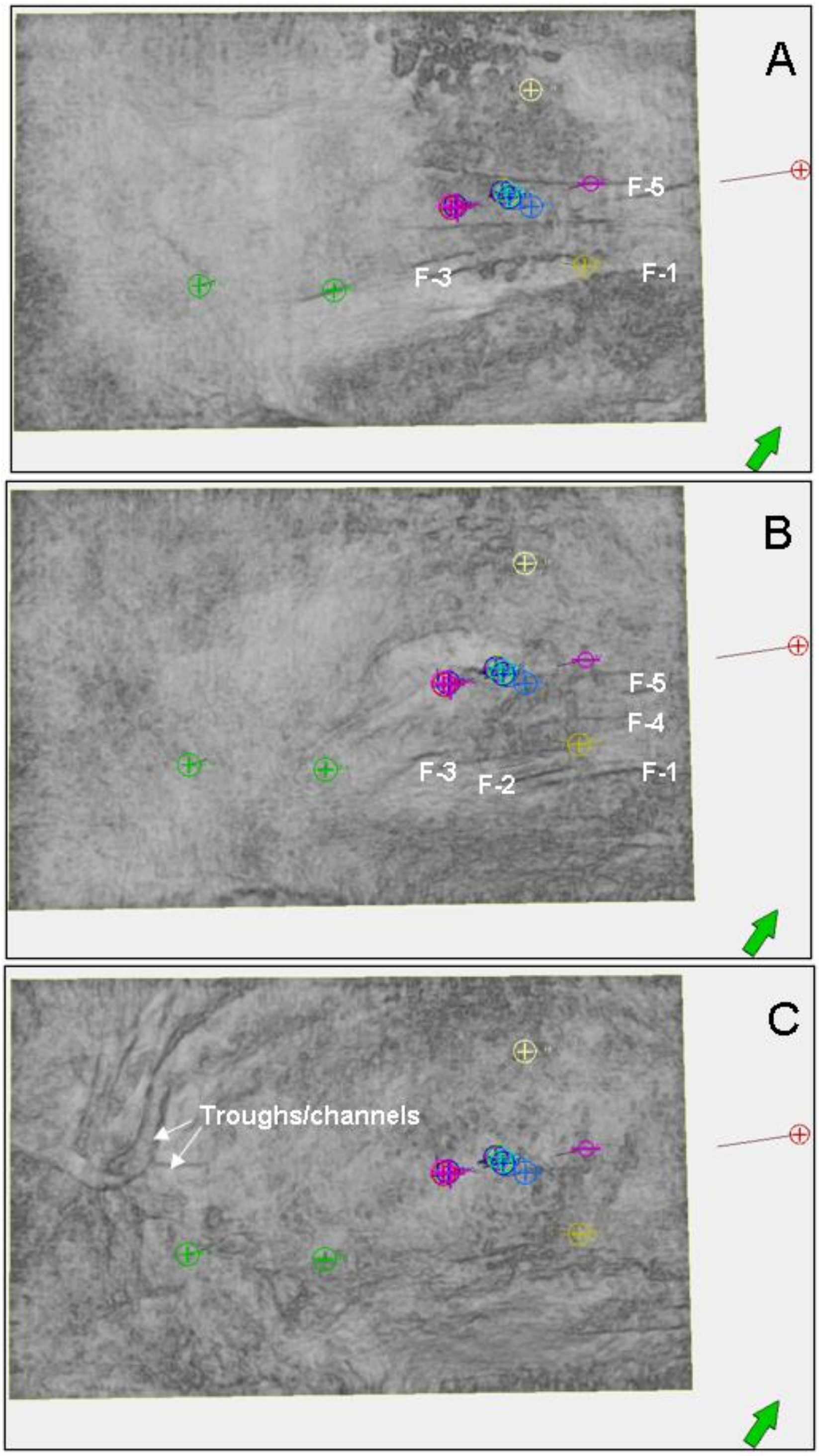


Fig. 16. Three amplitude coherency slices from the Stenlille-97 3D survey. The slices are from: (A) 786 ms TWT, crossing the Top Fjerritslev and with faults (F1, F3, F5) marked. (B) 976 ms TWT, crossing the Top Gassum and with faults (F1−F5) marked; (C) 1048 ms TWT, crossing mid-parts of the Gassum Formation (including SB4 and SB5), with troughs/ possible channels to the NW (white arrows). The faults interpreted at Top Fjerritslev and Top Gassum, and trough/channel features are also reflected in 2D sections (Figs. 15 and 17). See also Vosgerau et al. (2020).

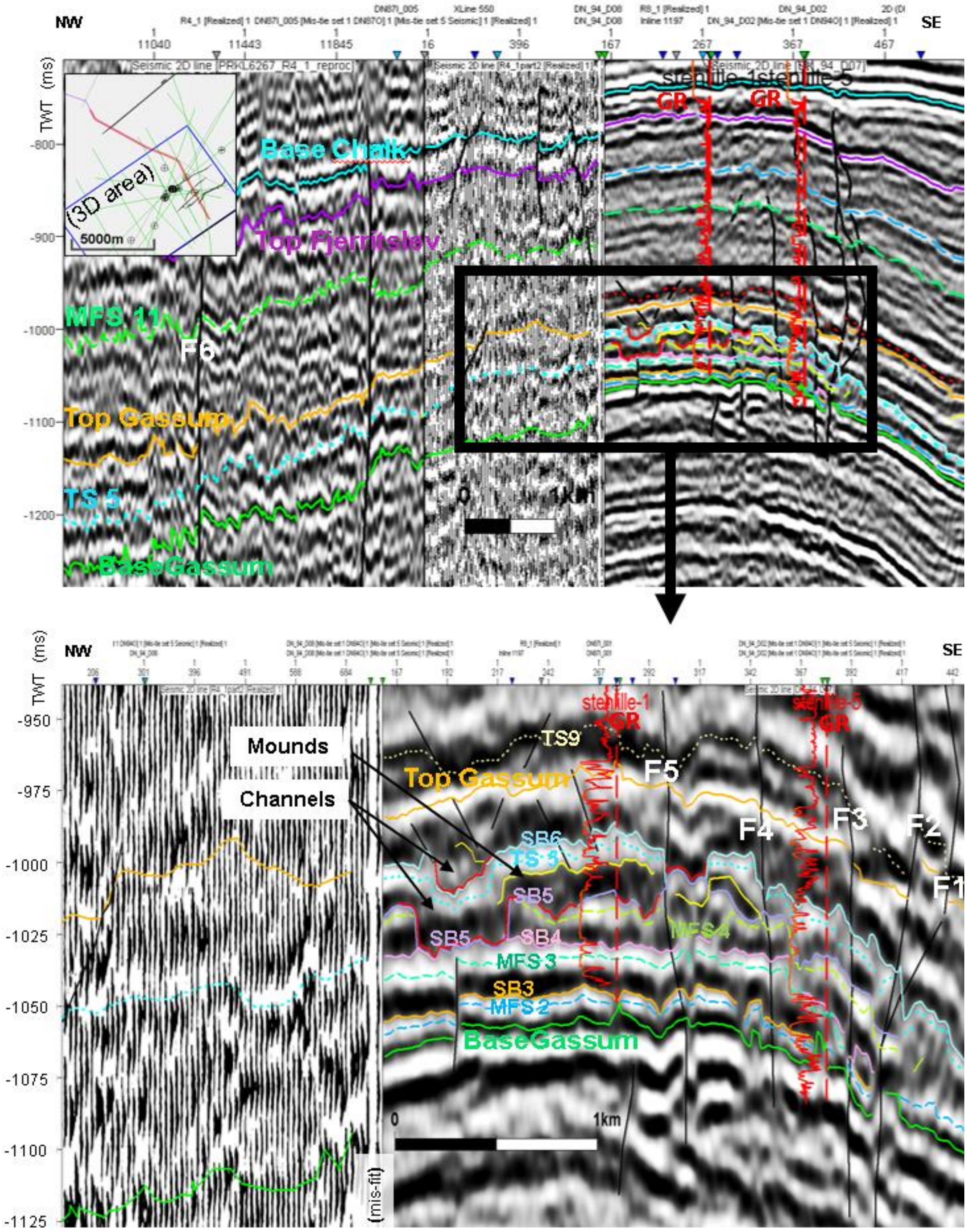


Fig. 17. Composite seismic section (lines R4_1 (left) and DN94_D07 (right)) NW to SE across the Stenlille structure, showing the difficult tie both with poor data NW of the 3D survey area and mis-fit. The lower section is a zoomed part of the upper section, and the DN94_D07 has been shifted up to fit the 3D survey. In the lower section details of seismic facies and features, including channels, downlaps, mounds and subtle faults (F1−F5), are interpreted with well ties to Stenlille-1 and -5. The detailed interpretation is not possible on the very poor scanned data to the left, and only the shown key surfaces (in the upper left section) are correlated to the Havnsø structure.

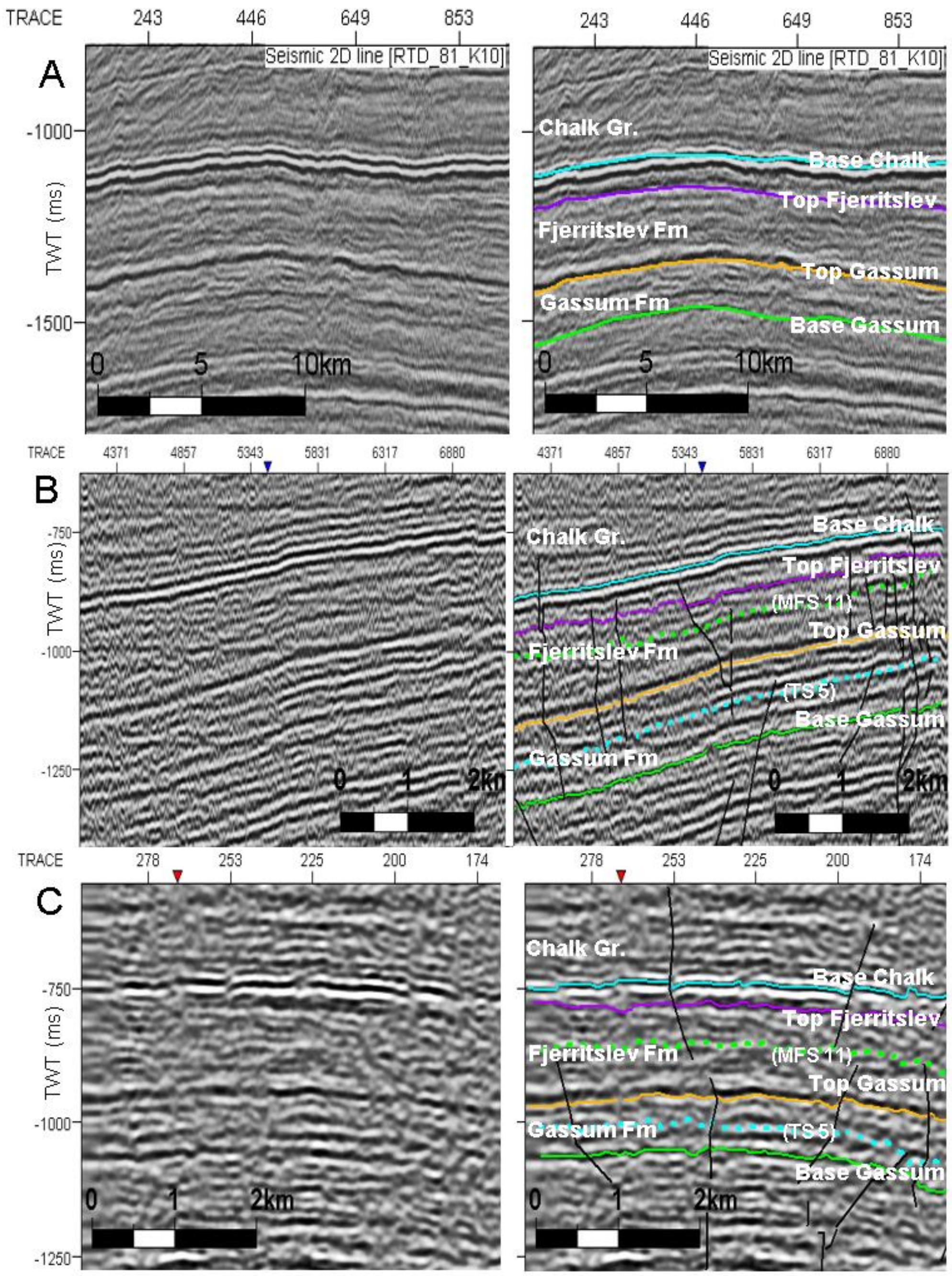


Fig. 18. Similar seismic facies of the Gassum Fm west of the Stenlille area, onshore and offshore: (A) Section RTD_81_K10 (part of Fig. 22), in Kattegat, 20 km NW of Sejerø and the Havnsø structure; (B) Section PRKL74A_303_Reproc. (part of Fig. 20, offshore), near top of the Havnsø structure; (C) Section SSL73_038_Reproc. (part of Fig. 20, onshore) at the top of the Havnsø structure. The Top Gassum is interpreted in a white through/zero-crossing, below a relatively strong, continuous black reflection on many sections, whereas the Base Gassum (Top Vinding) is a weaker black reflection. The internal reflections are many places characterized by minor mounds, short and discontinuous reflections and few troughs. The Gassum Fm interval, and in particular its lower part (at/below TS 5), is mostly more reflective than the Fjerritslev Fm interval.

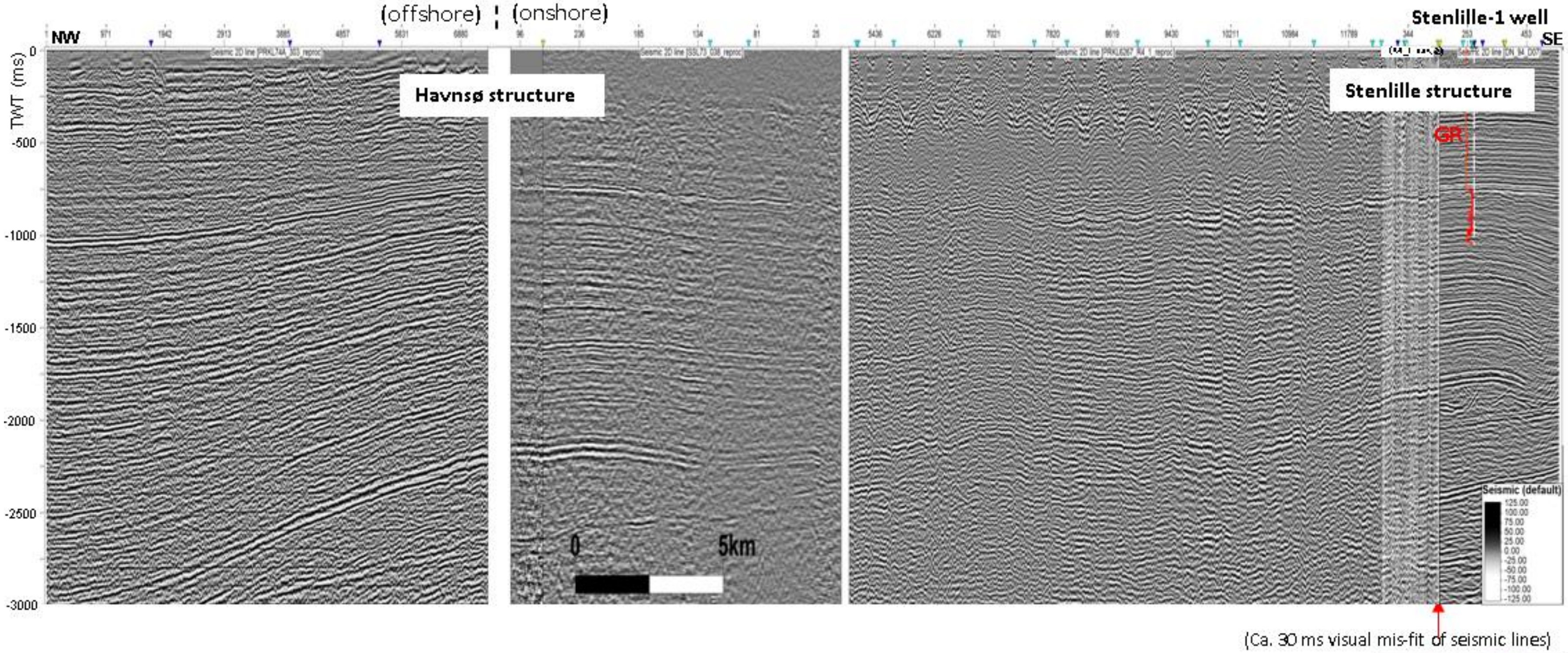
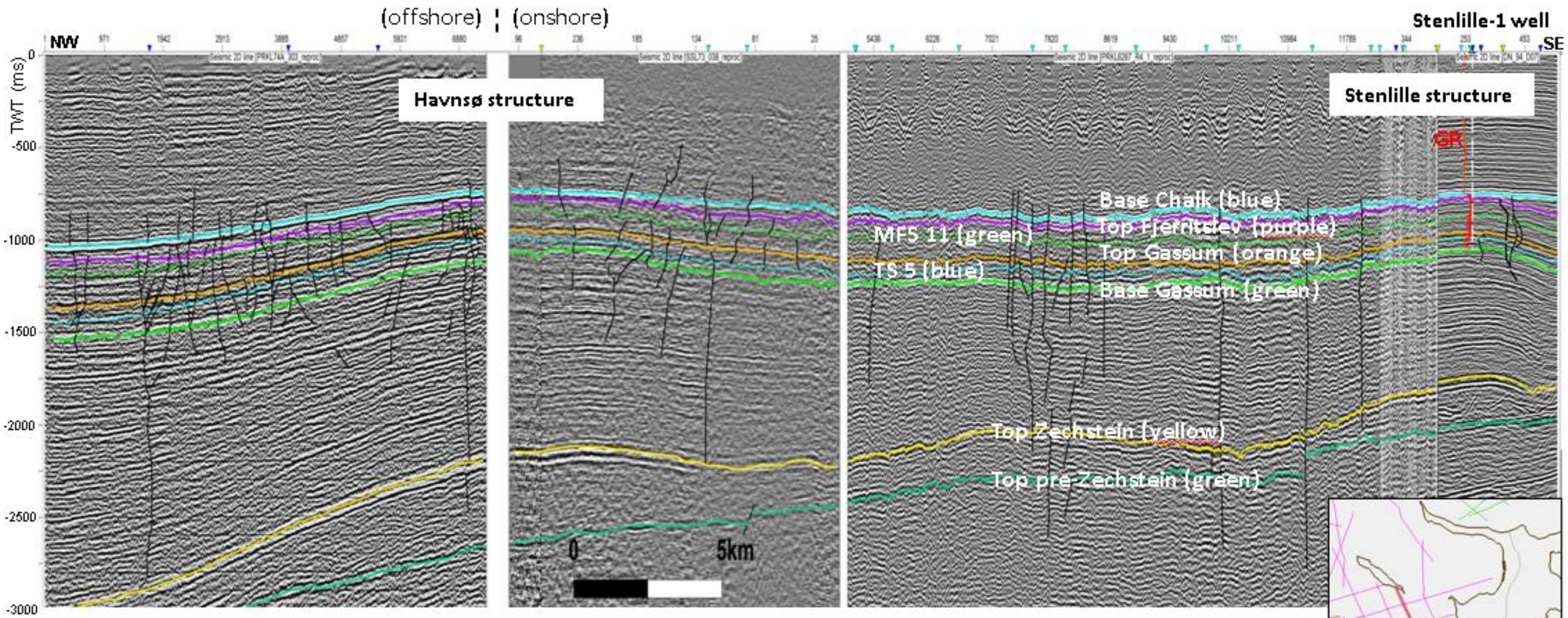


Fig. 19. Seismic composite section from the Stenlille structure (SE) to the Havnsø structure (NW). The same section is interpreted in Fig. 20. The seismic tie lines from the Stenlille to the Havnsø area are variable in quality, but reprocessing of the three left sections (see ”reproc” in line headings) has improved data slightly and made correlation possible.
The left lines seem to fit, but there is a visual 30 ms mis-fit of data from the line DN94_D07 (right) in the Stenlille area to the line R4_1 part 2, at the red arrow. In the Stenlille area, the 3D survey is c. 15 ms shallower than lines of the DN94 survey (Fig. 4A).



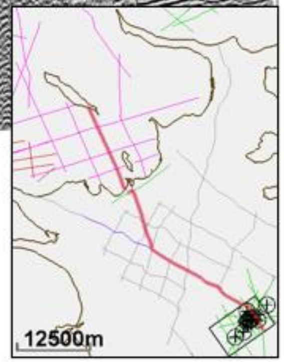


Fig. 20. Seismic composite section from the Stenlille structure (SE) to the Havnsø structure (NW).

Observations from the Stenlille area towards NW into the Havnsø structure:

- The Gassum Fm thickens westwards.
- The lower part of the Gassum Fm below TS 5 apparently keeps or slightly increases in thickness westwards as the formations does, but it thins slightly in the Havnsø structure.
- Mounds and troughs appearently become sparse/disappear and few bright events occur.
- Fjerritslev Fm and its lower part below MFS 11 thickens.
- Thickening of the Fjerritslev Fm on both sides of the Havnsø structure, on which onlap/downlap may indicate influence by structural movements and subsidence at its flanks.
- Minor faults from Top Gassum and up through the Fjerritslev Fm and into the lowermost Chalk Group are mostly extensional, but also with compression/transpressional components, including vertical faults with minor thrusting and flower structures over both main structures.

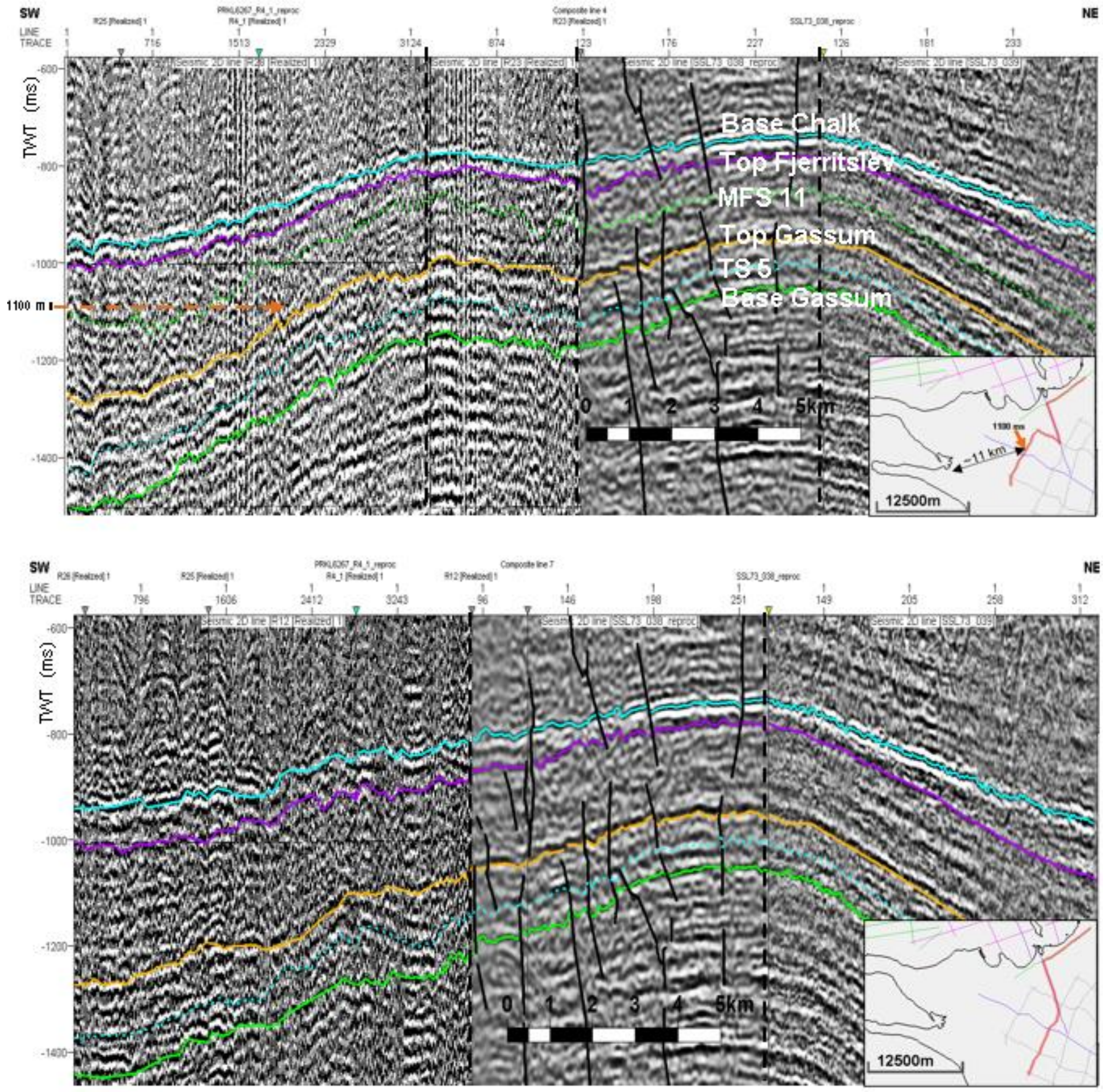


Fig. 21. Two composite seismic sections across the Havnsø structure from SW to NE. The 1100 ms TWT level at the Top Gassum horizon is the closing contour of the Top Gassum mapped surface (Fig. 26), and the distance from Kalundborg to this point is c. 11 km in the upper section.

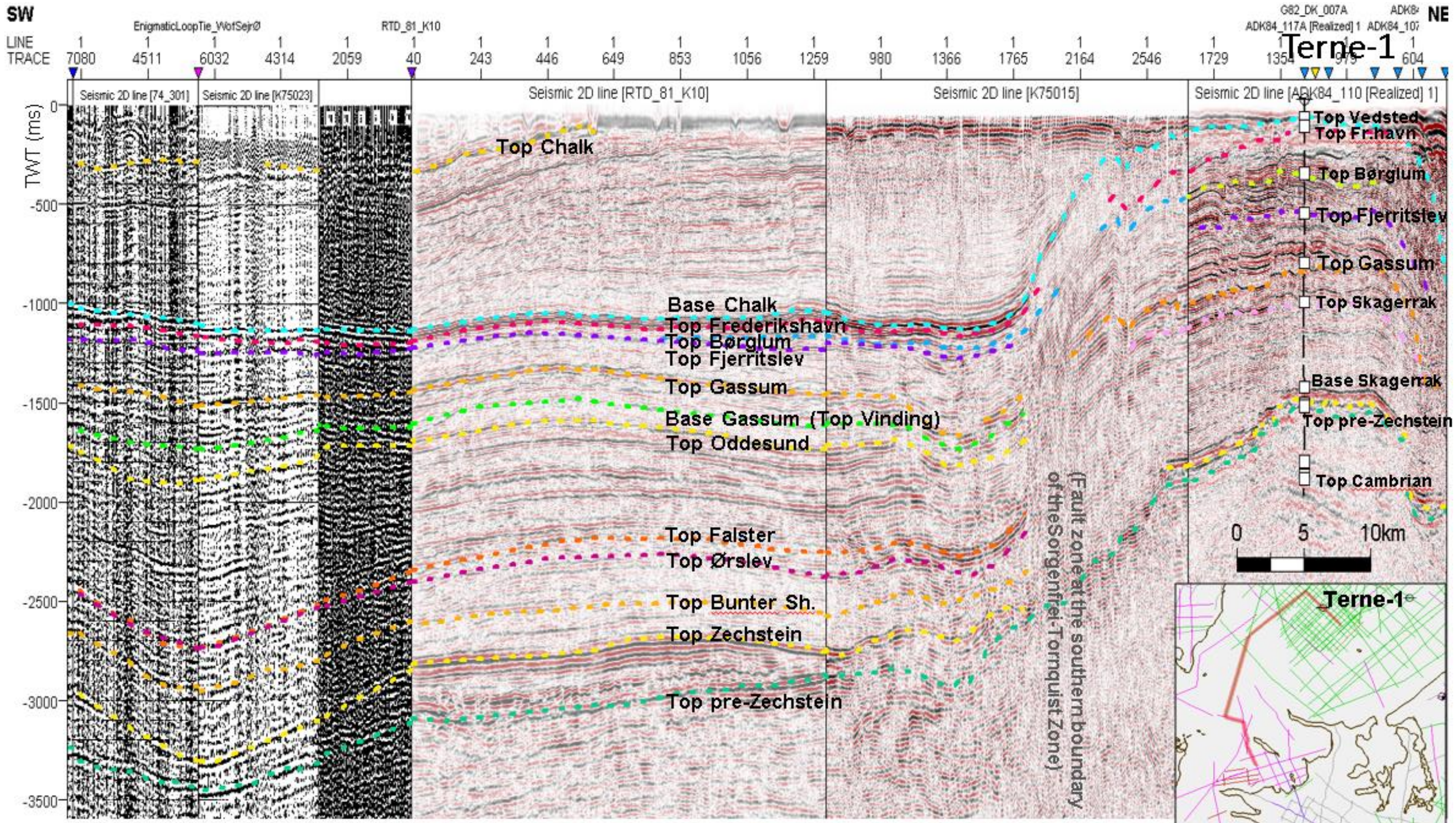


Fig.22. Seismic-well-tie from the Terne-1 well to Sejerø Bugt, north of the Havnsø structure. Challenges include poor data towards the Sejerø Bugt and complex faulting across the Sorgenfrei-Tornquist Zone with ties of horizons to the Terne-1 well.

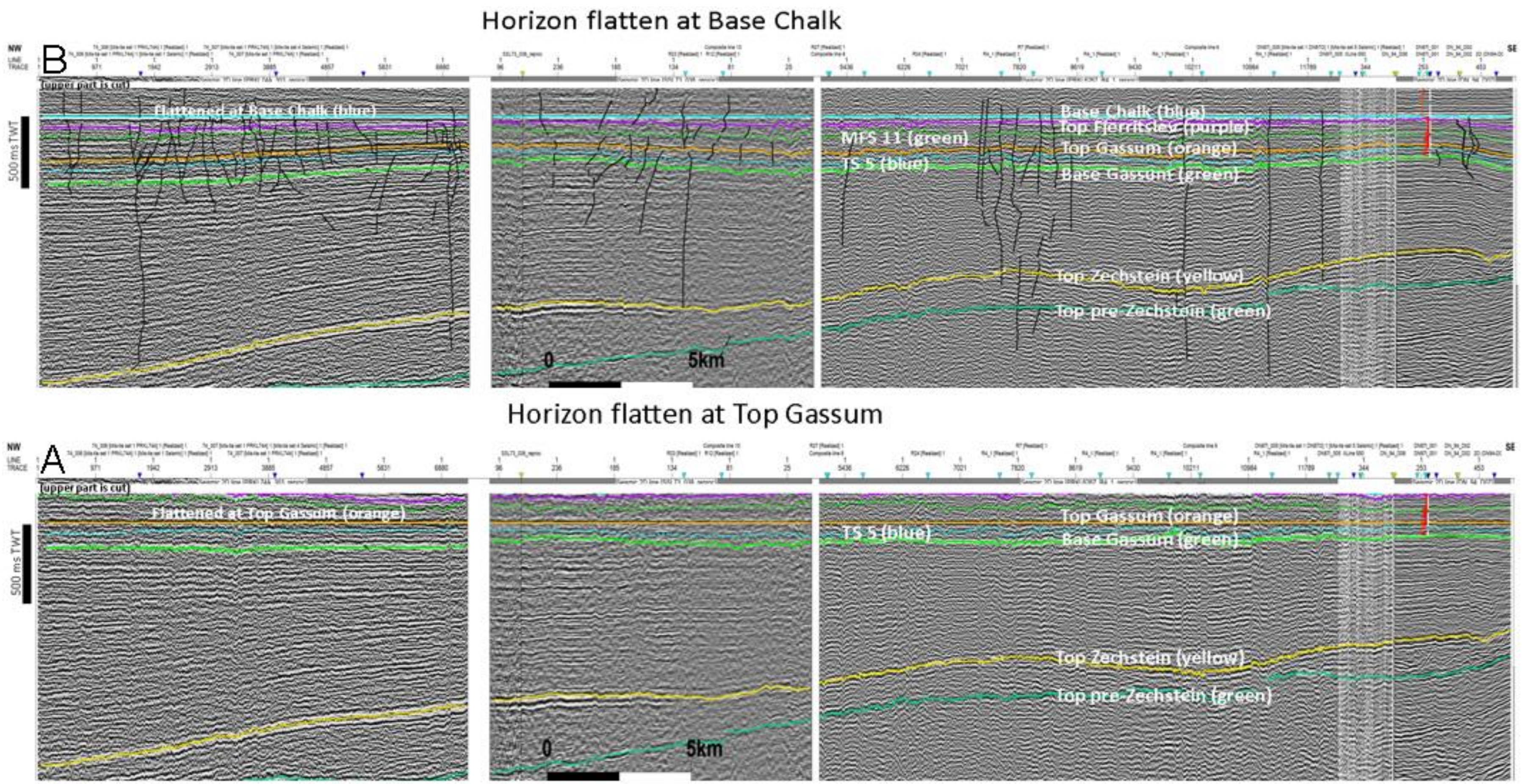


Fig. 23. Horizon flatten of Fig. 20 at (A) Top Gassum and (B) Base Chalk. Observations from Stenlille area towards NW into the Havnsø structure:

- The deep structures (Zechstein) increase and the basin subsides towards west from the Top Gassum (A) to the Base Chalk (B) time.
- The Fjerritslev Fm and in particular its lower part below MFS 11 thickens westwards.
- Thickening of the Fjerritslev Fm on both sides of the Havnsø structure and onlap/downlap may indicate influence by structural movements.
- The Fjerrtitslev Fm is slightly affected by structural movements and faults were formed near Top Fjerritslev Fm to near base Chalk time.
- Minor faults from the Gassum Fm through the Fjerritslev Fm and into the lower Chalk Group are mostly extensional with compression/transpressional components/flower structures.

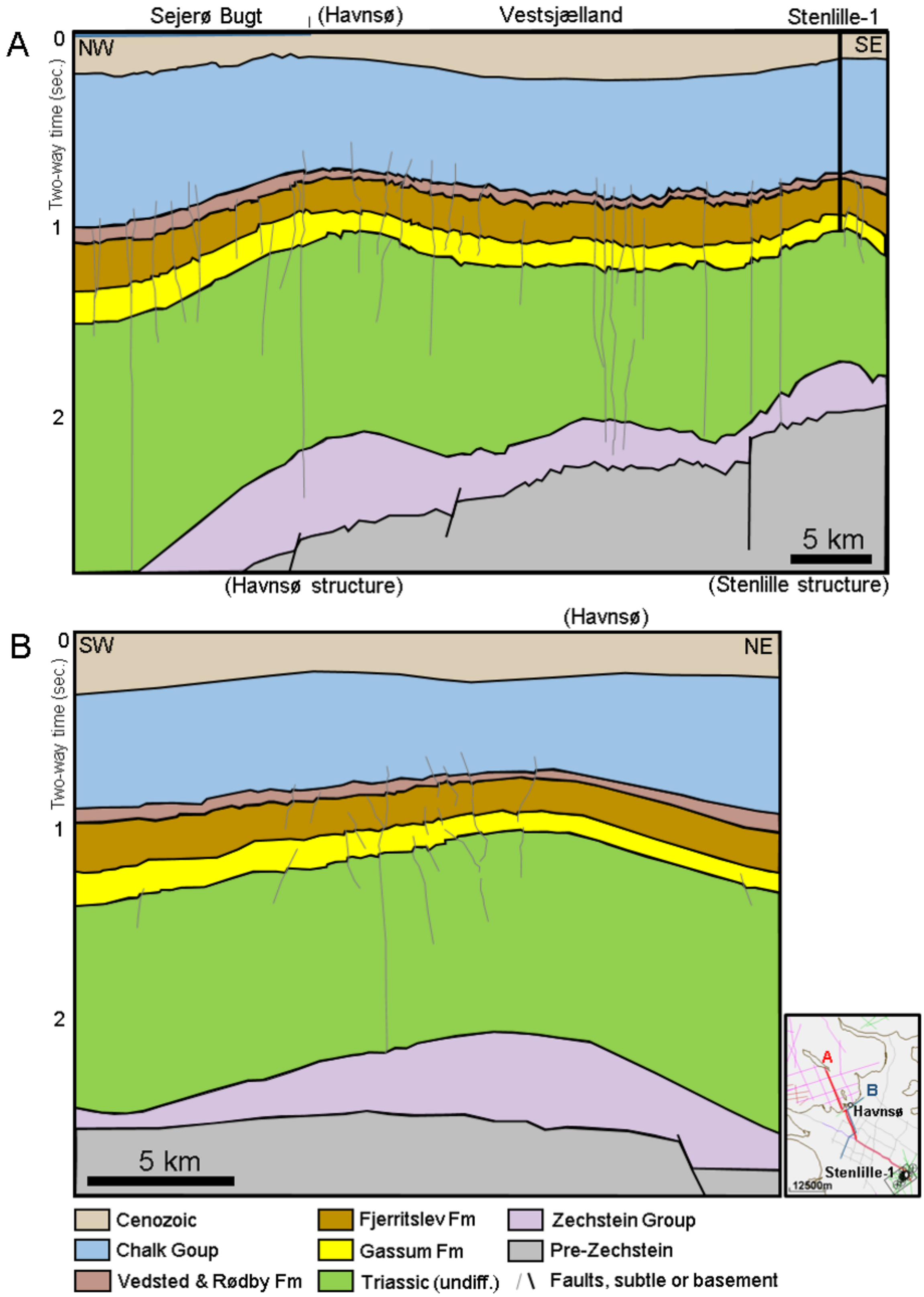


Fig. 24. Schematic geological sections: (A) NW-SE section through the Havnsø and Stenlille structures with tie to the Stenlille-1 well. (B) SW-NE section through the Havnsø structure. The scale is in second two-way time (TWT). The figures are based on Figures 20 and 21, respectively. In the Stenlille-1 well the Top Gassum Formation is at ~965 ms TWT/~1507 m MD.

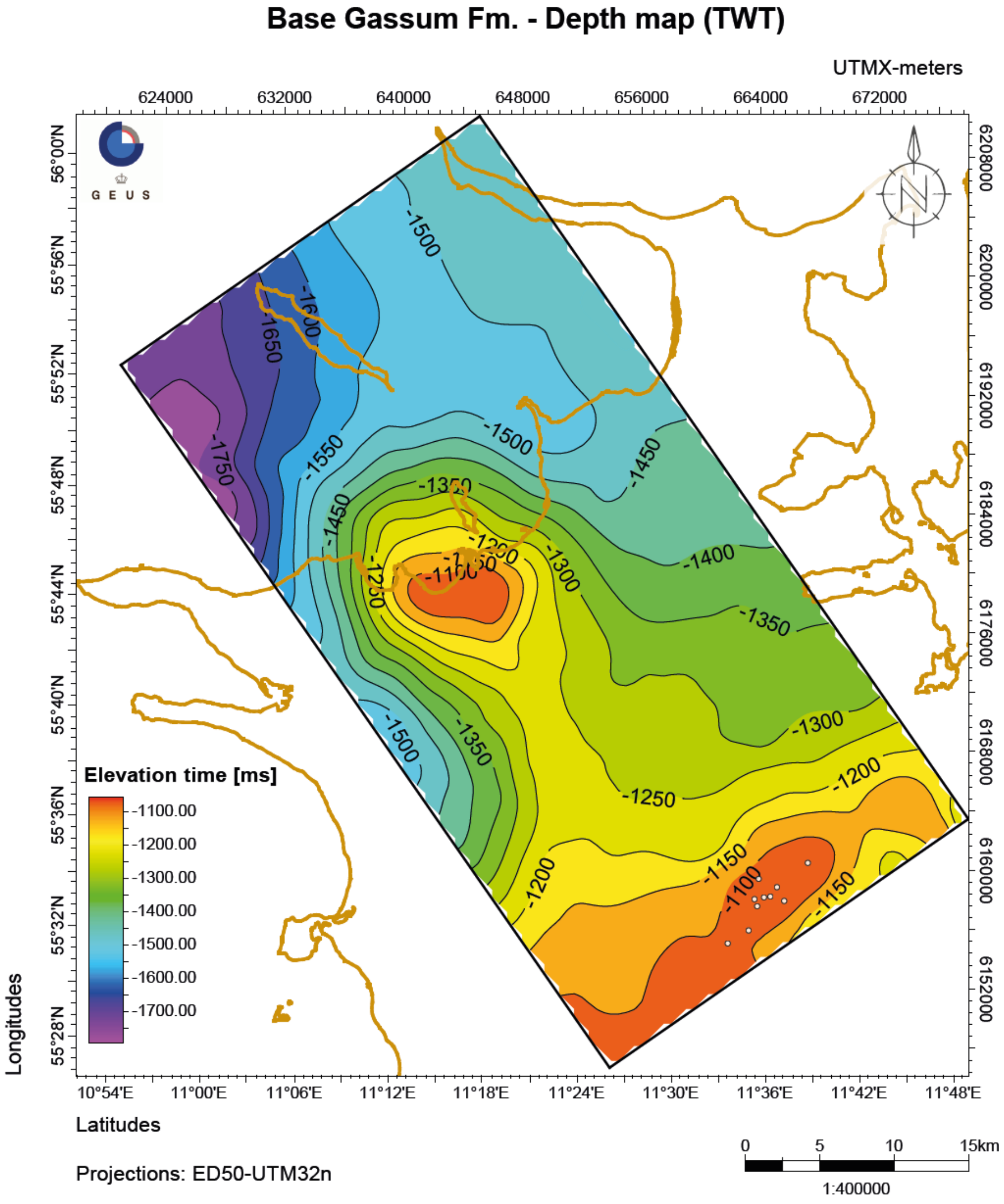


Fig. 25. Base Gassum Fm – Depth map in milliseconds (ms) two-way time (TWT).

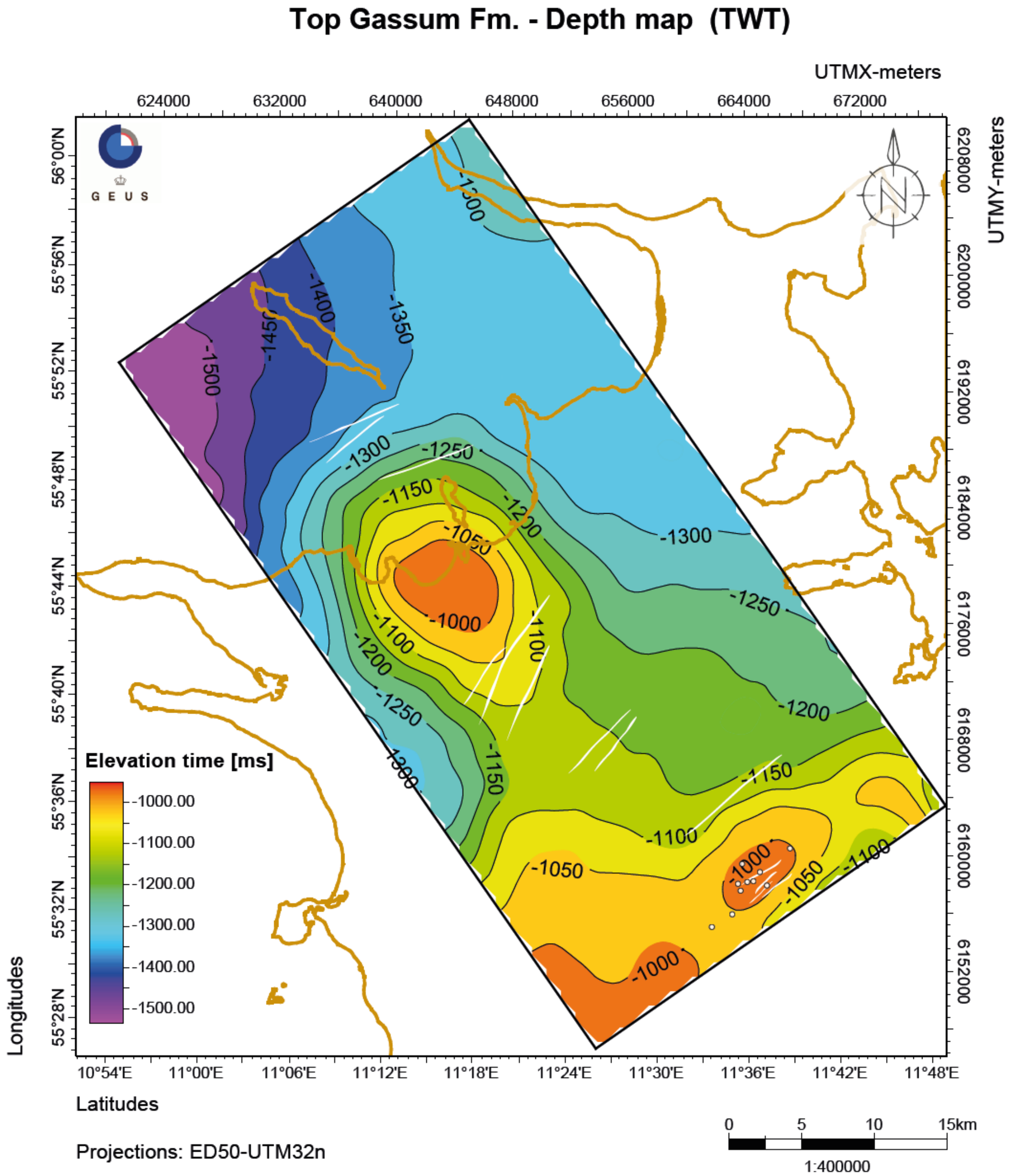


Fig. 26. Top Gassum Fm – Depth map in milliseconds (ms) two-way time (TWT). The closing contour is at 1100 ms TWT. The top-point of the Havnsø structure is at ~935 ms TWT. The top-point of the Stenlille structure is at ~965 ms TWT. White lines are faults.

Trangressive surface 5 (TS 5) - Depth map (TWT)

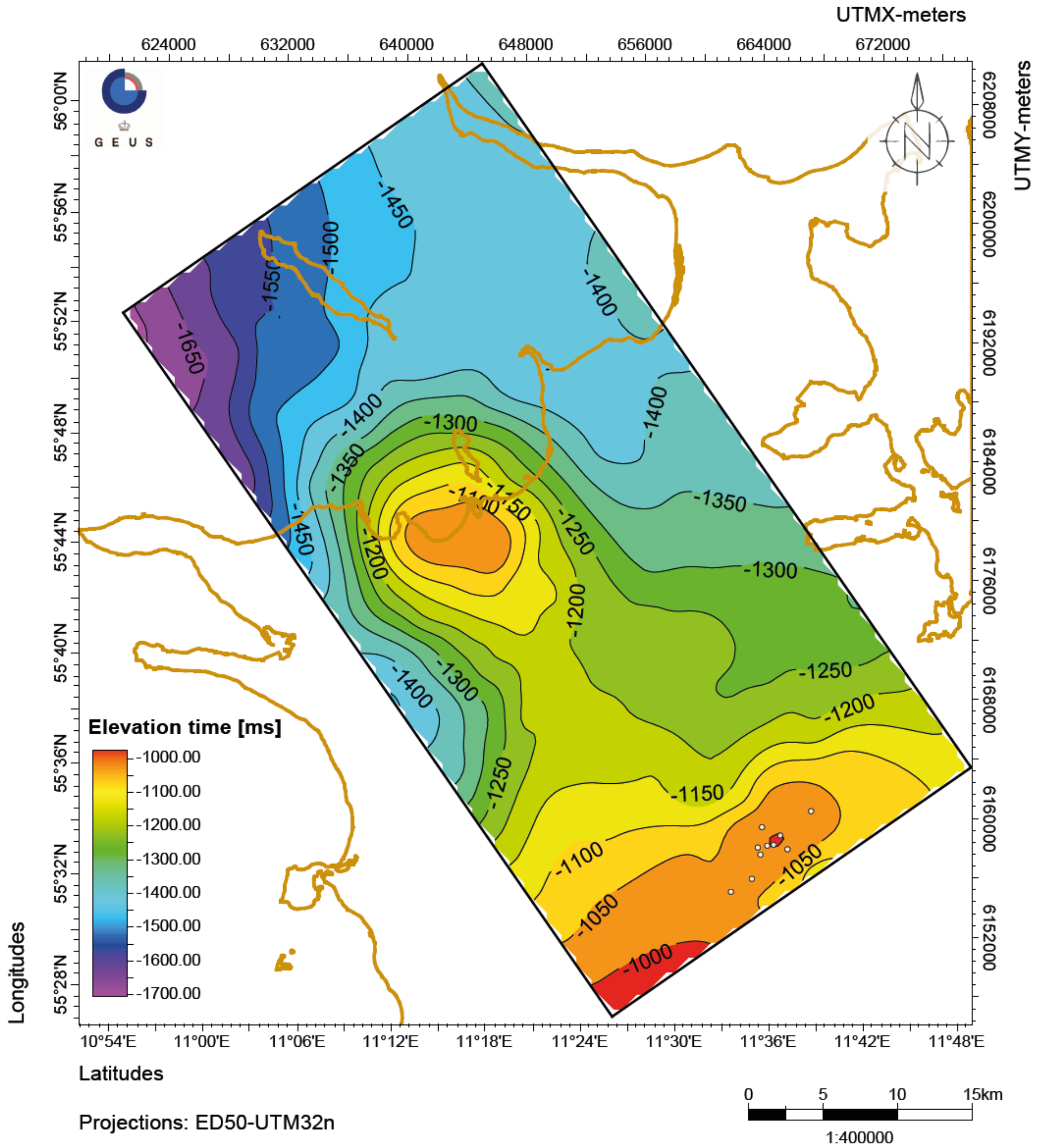


Fig. 27. Transgressive surface 5 - TS 5 - Depth map in milliseconds (ms) two-way time (TWT). The TS 5 occurs in Sequence 5 in the middle part of the Gassum Formation, and it tops a thick sandstone succession (Fig. 13).

Maximum flooding surface 11 (MFS 11) - Depth map (TWT)

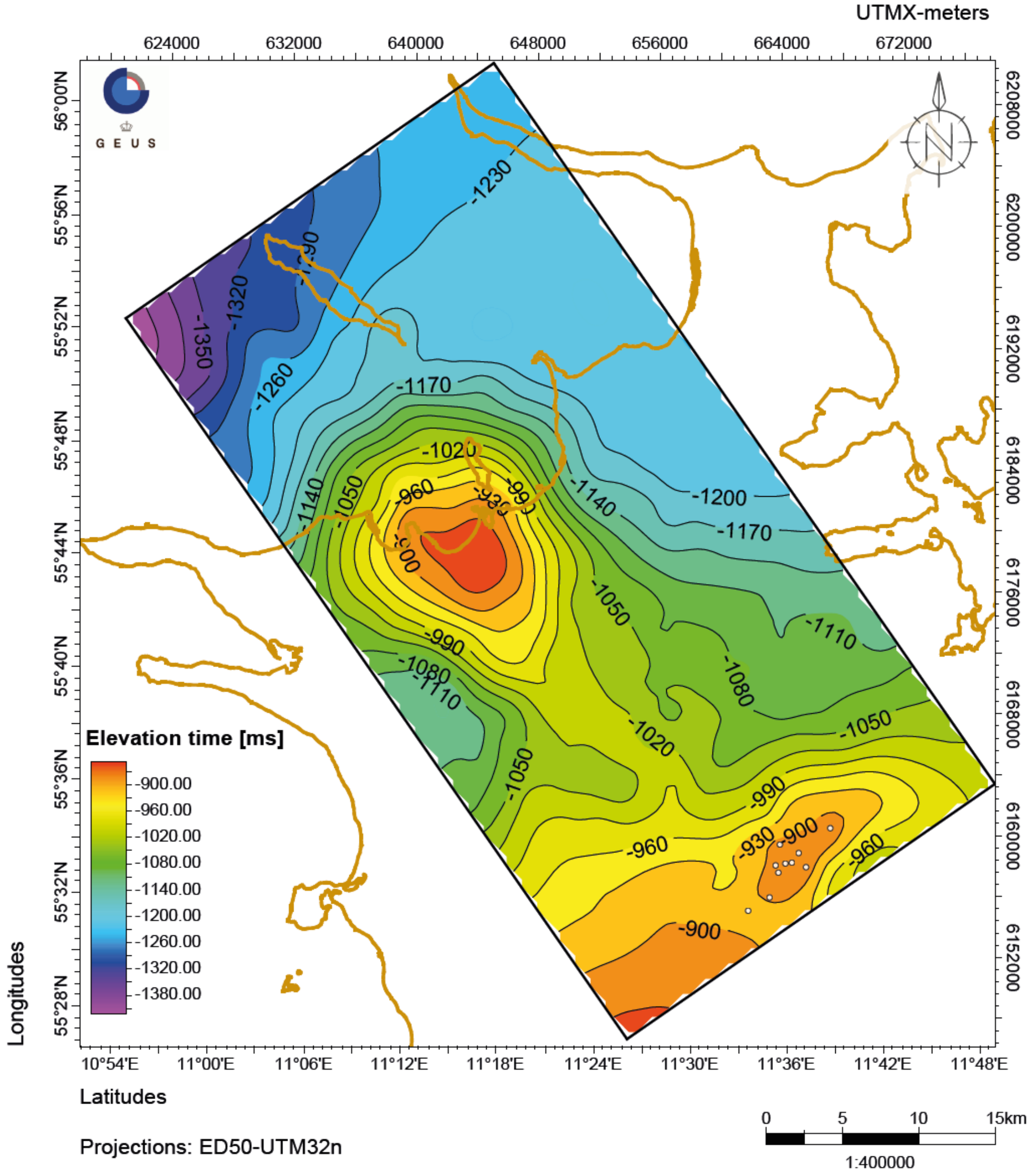


Fig. 28. Maximum flooding surface 11 - MFS 11 - Depth map in milliseconds (ms) two-way time (TWT).

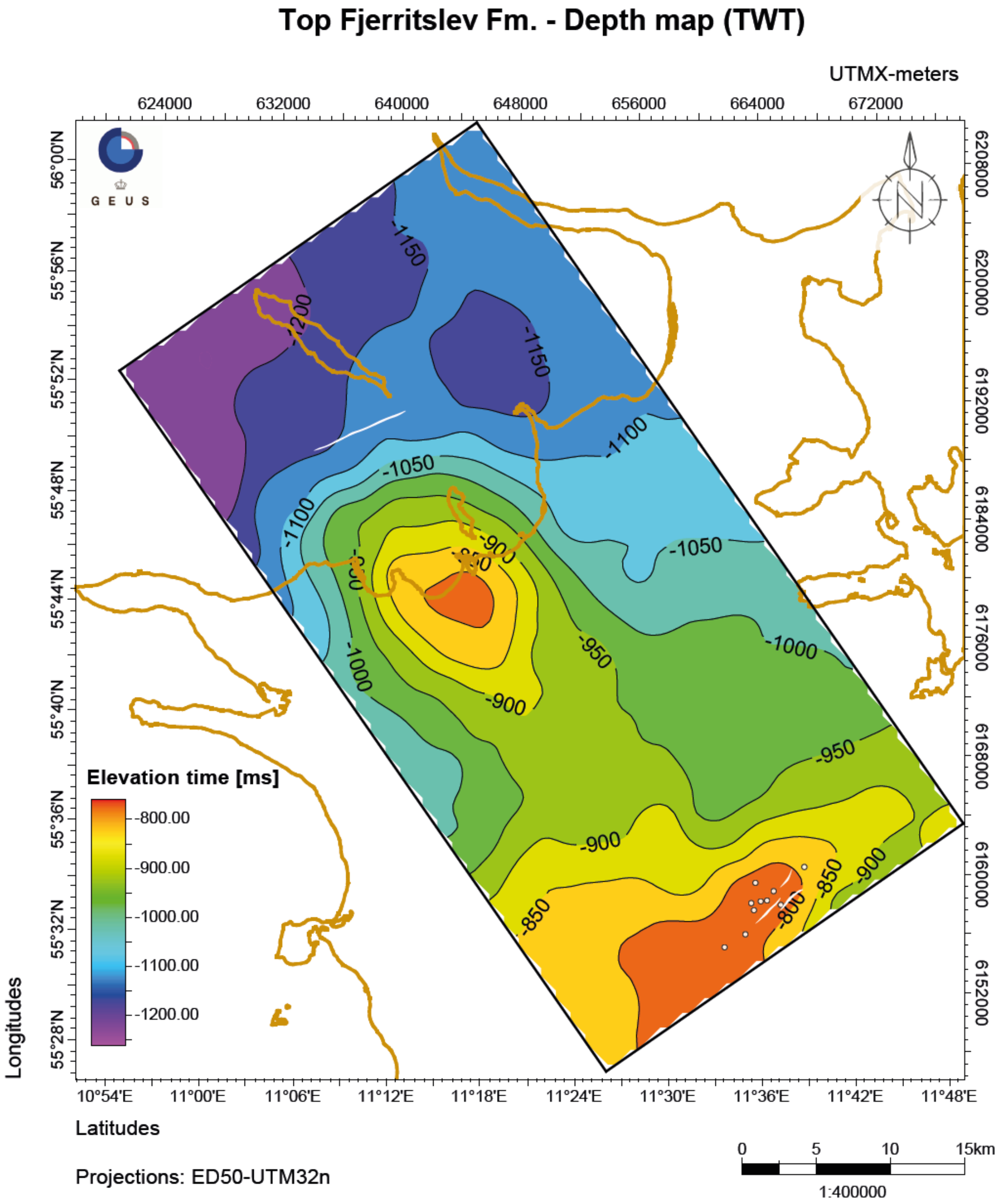


Fig. 29. Top Fjerritslev Fm – Depth map in milliseconds (ms) two-way time (TWT). The top-point of the Havnsø structure is at ~775 ms TWT. The shallowest point of the Stenlille structure is at ~768 ms TWT. White lines are faults.

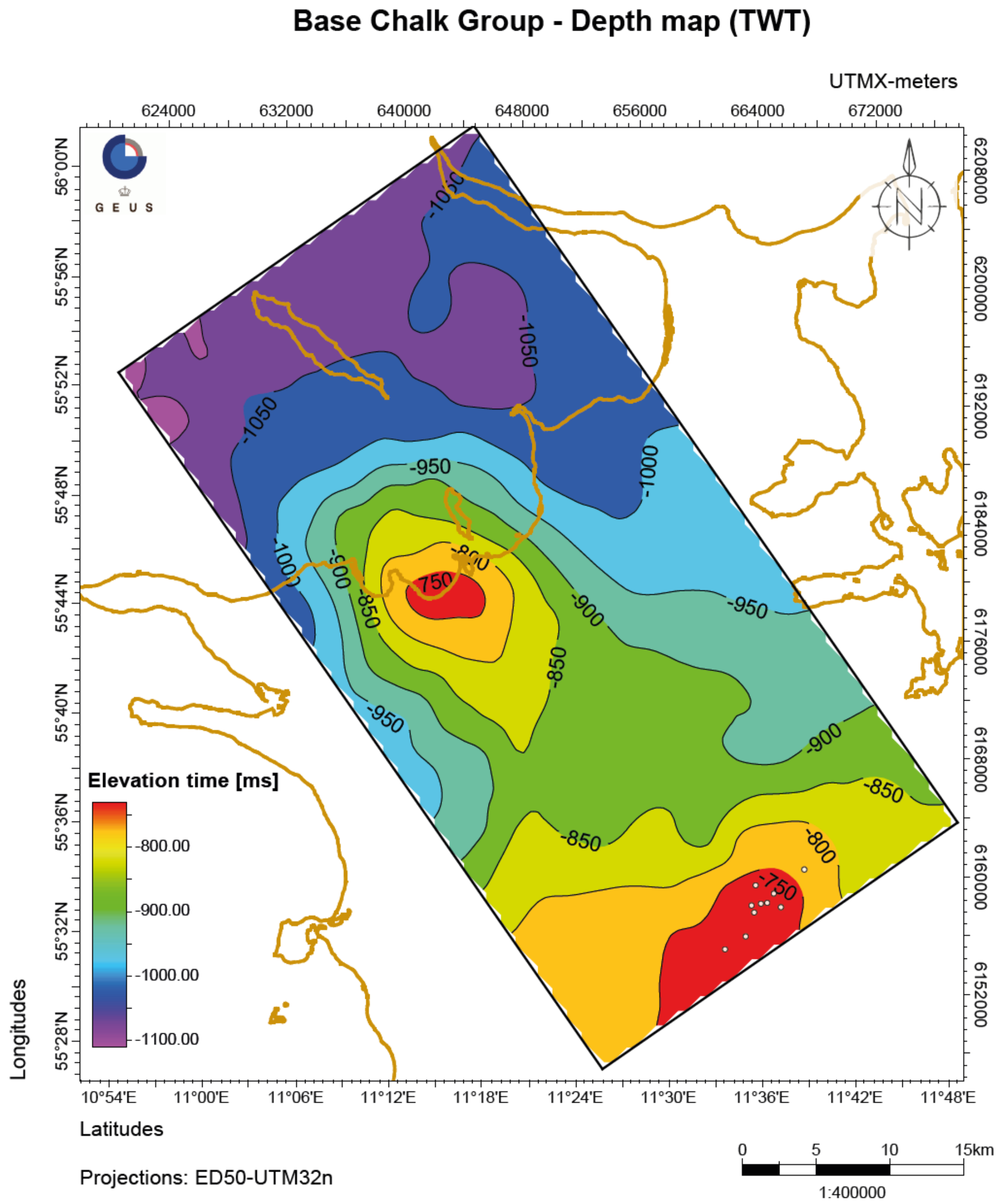


Fig. 30. Base Chalk Group – Depth map in milliseconds (ms) two-way time (TWT).

Gassum Fm. - Thickness map (TWT)

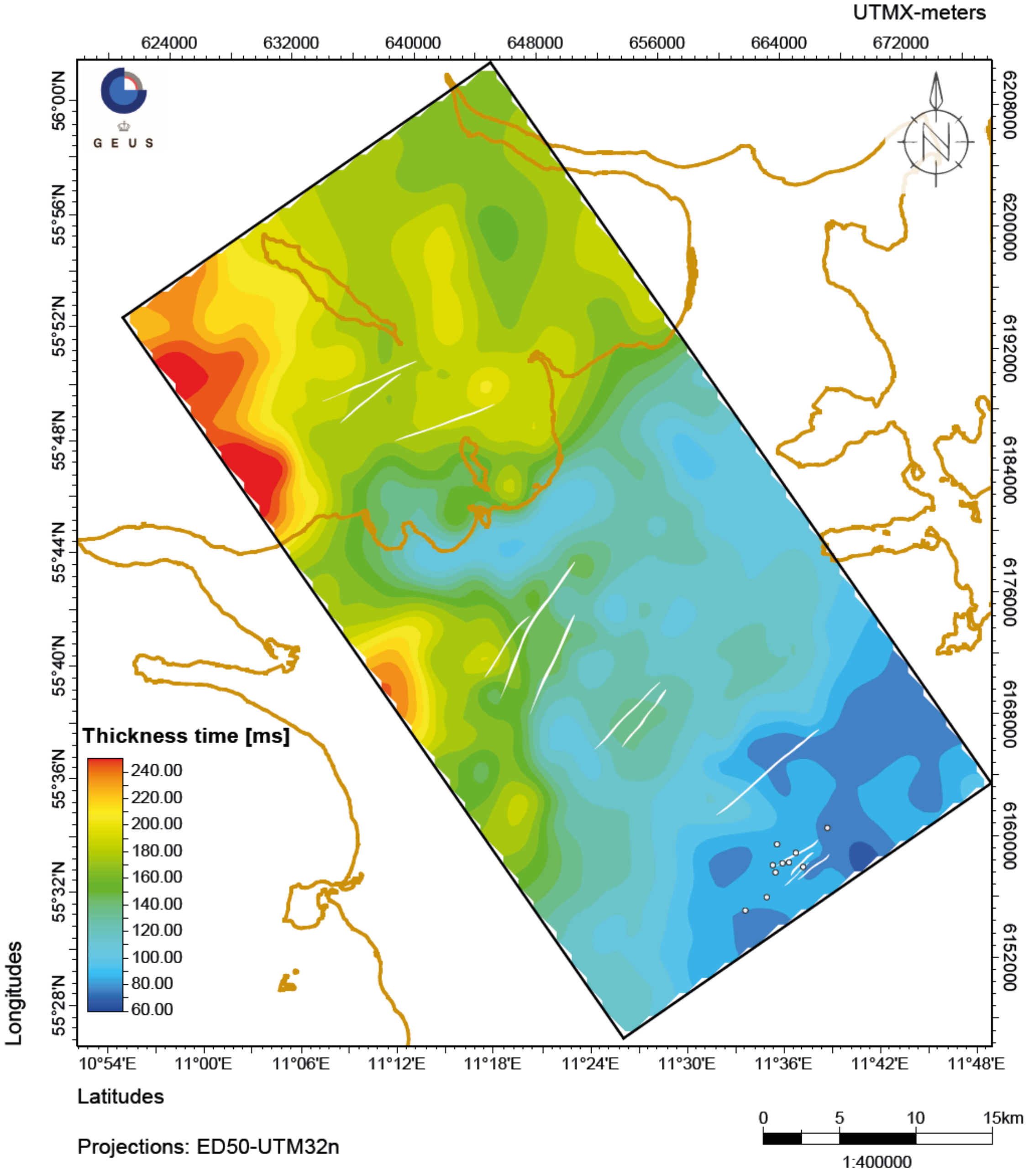


Fig. 31. Gassum Fm – Thickness map in milliseconds (ms) two-way time (TWT). The map shows the thicknesses in TWT between the Top Gassum and the Base Gassum surfaces. White lines are faults.

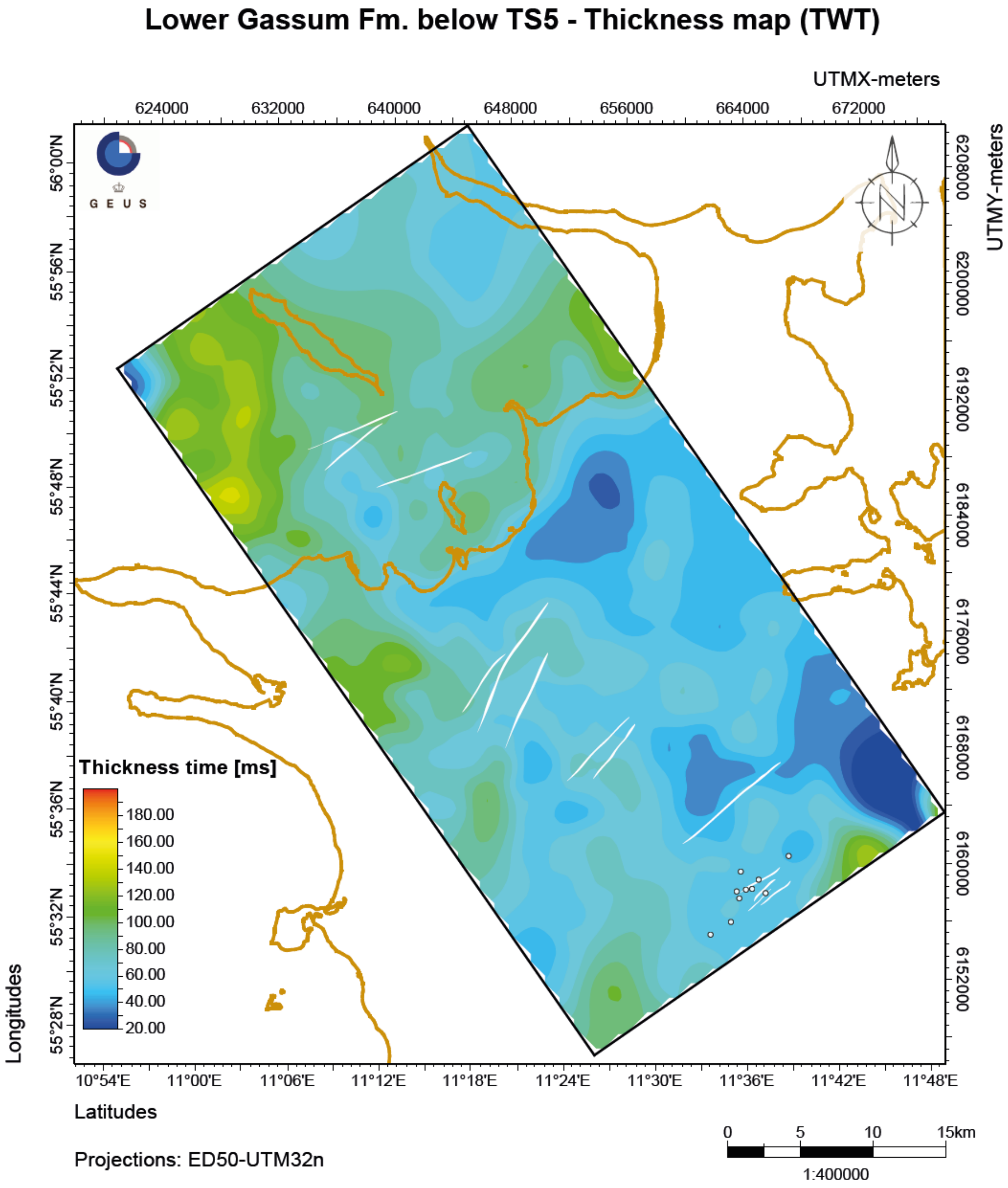


Fig. 32. Lower Gassum Fm below TS 5 – Thickness map in milliseconds (ms) two-way time (TWT). The map shows the thicknesses in ms TWT between the TS 5 and the Base Gassum surfaces. White lines are faults.

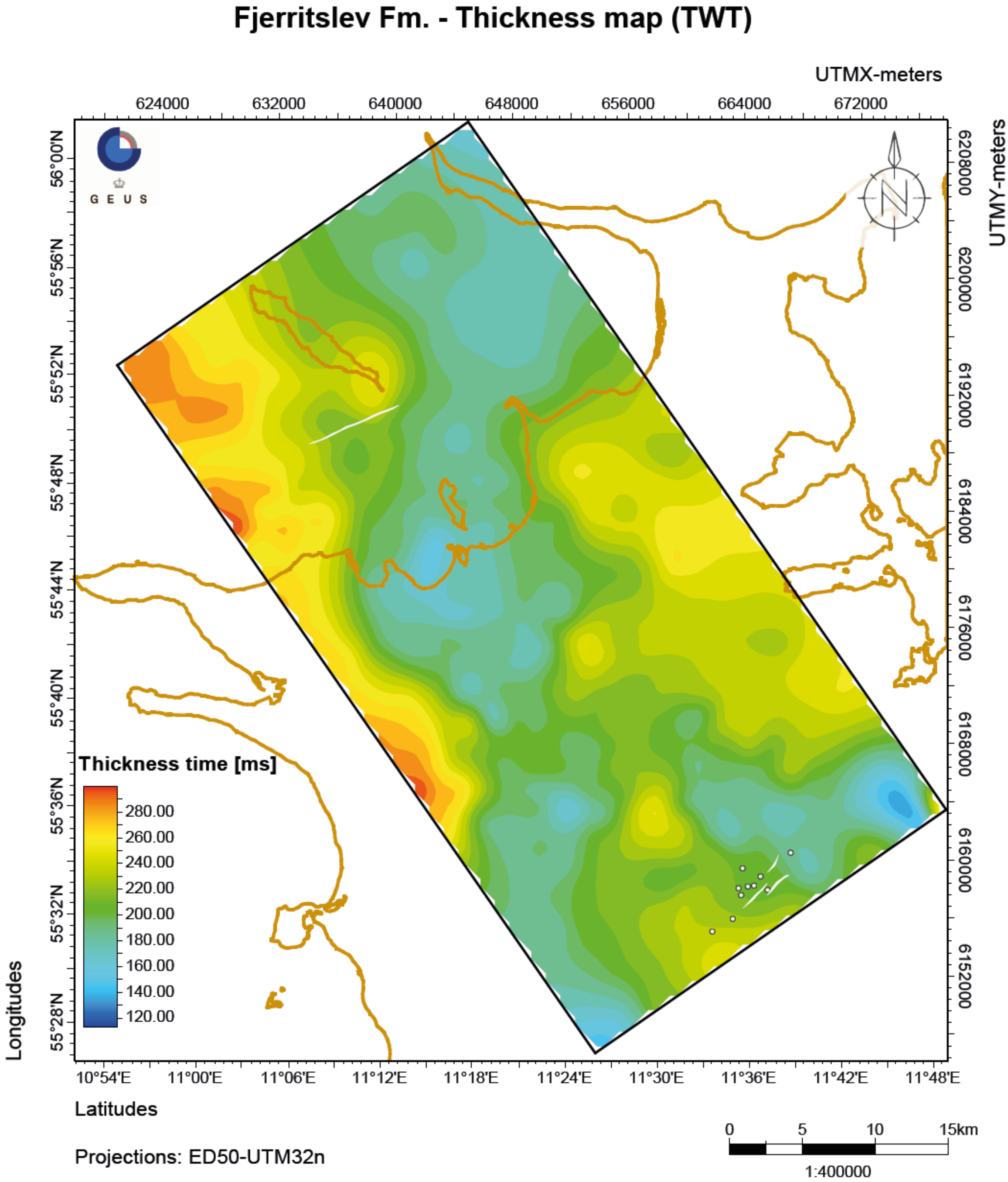


Fig. 33. Fjerritslev Fm – Thickness map in milliseconds (ms) two-way time (TWT). The contour interval is 50 ms TWT. The map shows the thickness in TWT between the Top Fjerritslev and the Top Gassum surfaces. White lines are faults.

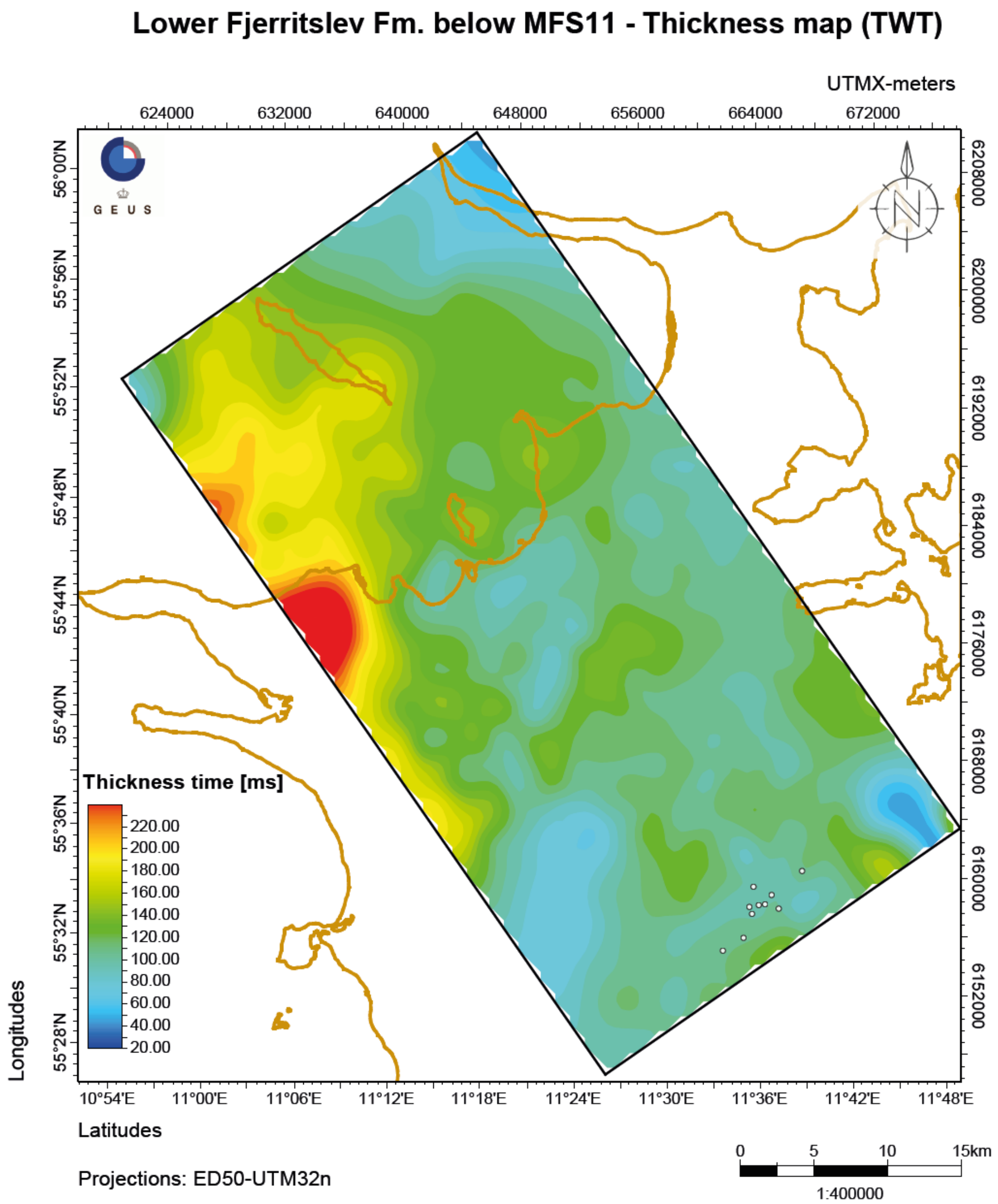
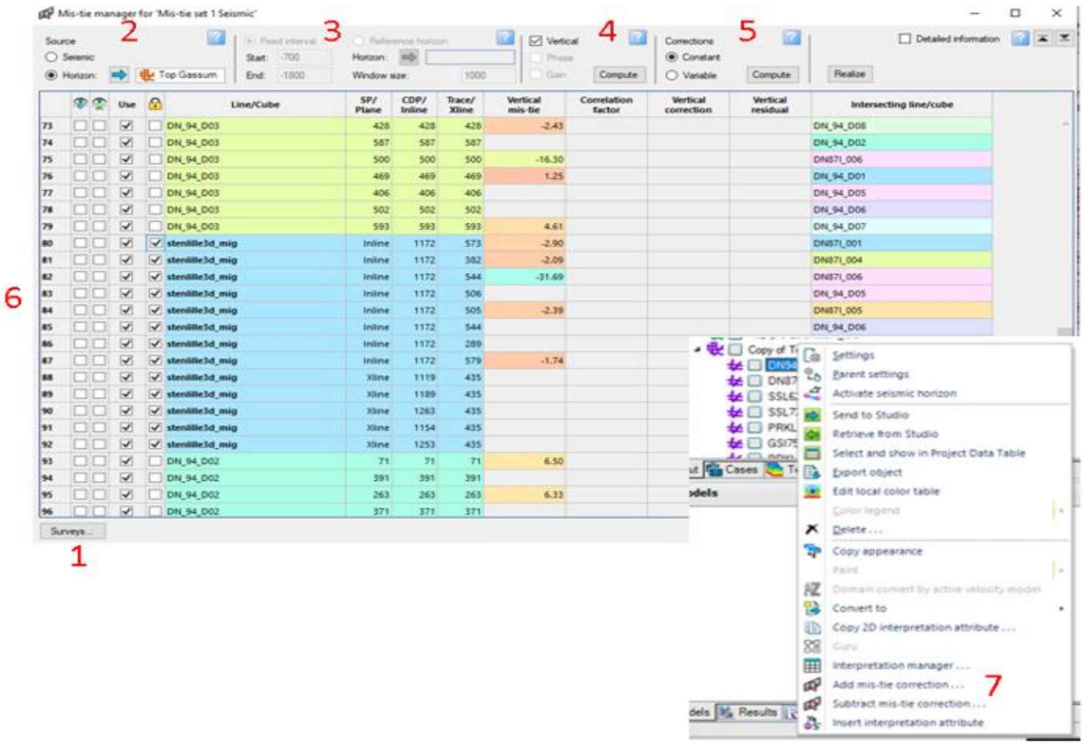


Fig. 34. Lower Fjerritslev Fm below MFS 11 – Thickness map in milliseconds (ms) two-way time (TWT). The map shows the thicknesses in TWT between the MFS 11 and the Top Gassum surfaces.

Appendix

Appendix 1(A) – Petrel mis-tie analysis



The Petrel mis-tie manager was used to analyze and correct possible mis-ties (in terms of vertical shift, phase or gain) between seismic within a survey or across different surveys. A new mis-tie set contains all the intersections between the involved 2D seismic lines and existing lines from 3D cubes. When a mis-tie set is created new virtual mis-tie corrected versions of all the involved seismic is created.

1. The surveys included in the table is selected when the mis-tie set is first created. The survey set and their associated vintages can be changed by selecting the “Surveys” button.

2. Choose the source of the mis-tie computation as either the seismic itself or a horizon with interpretations that possibly mis-ties at the intersections.

3. If the source is the seismic itself, choose the vertical window of where the analysis should be performed. This can be either a fixed vertical window or it can follow a reference horizon.

4. Choose which properties (vertical shift, phase, gain) that should be computed for each intersection point.

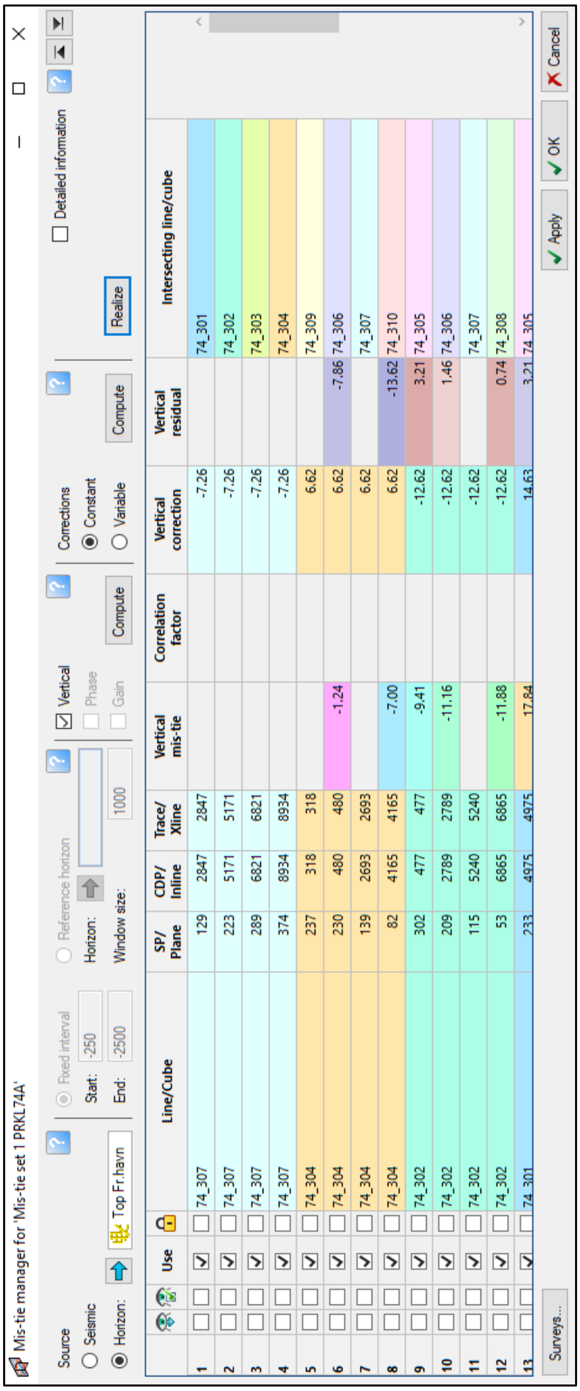
5. Choose how the actual correction should apply, either as a constant value for each seismic instances, or variable according to the mis-tie along the line.

6. For the corrections computed, seismic may be selected as reference instances by checking the corresponding lock column. Locked instances will be kept as is and get zero correction values.

7. Corrections from the mis-ties manager can be added or subtracted from horizon interpretations.

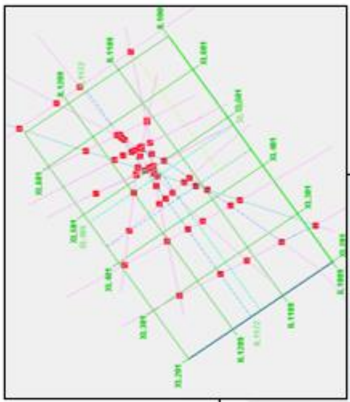
Appendix 1A. Procedure of the Petrel mis-tie analysis.

Appendix 1(B) – Petrel mis-tie analysis

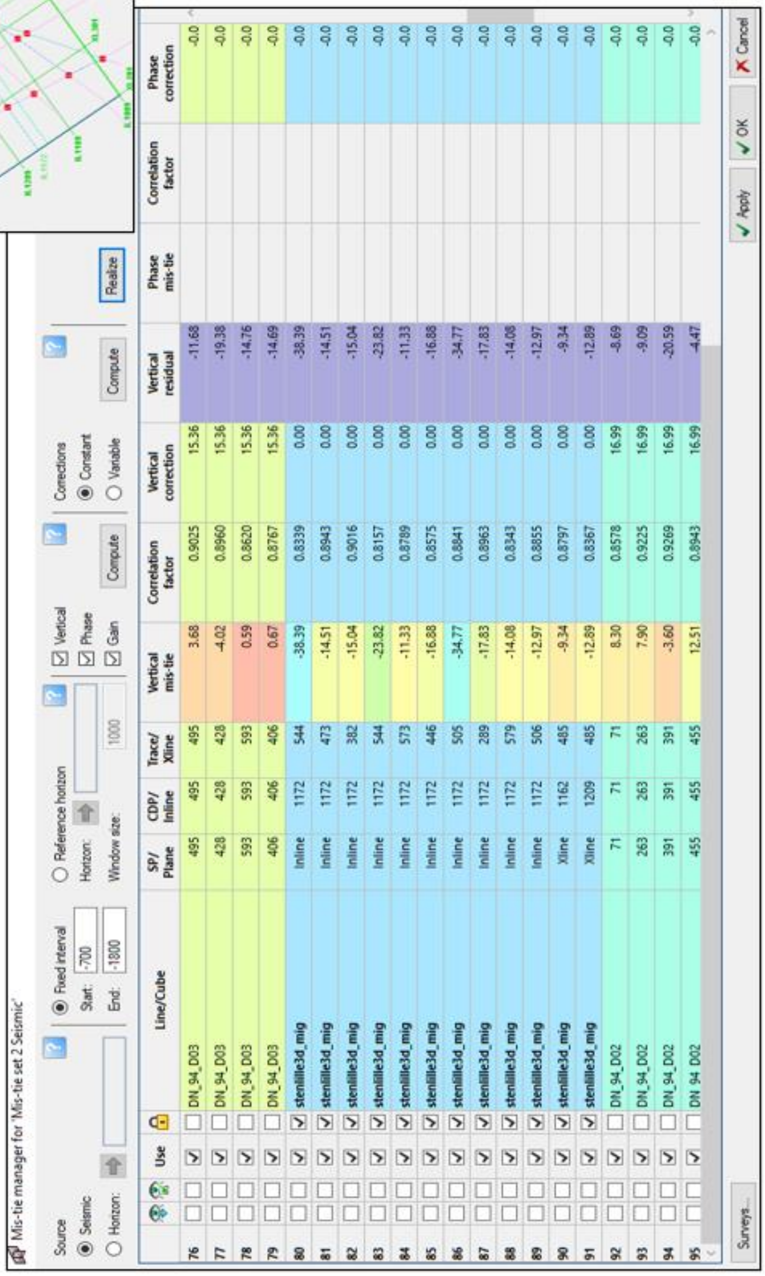


Appendix 1B. Example of mis-tie analysis (constant shift) between lines of the same 2D survey: PRKL74A (offshore).

Appendix 1(C) – Petrel mis-tie analysis



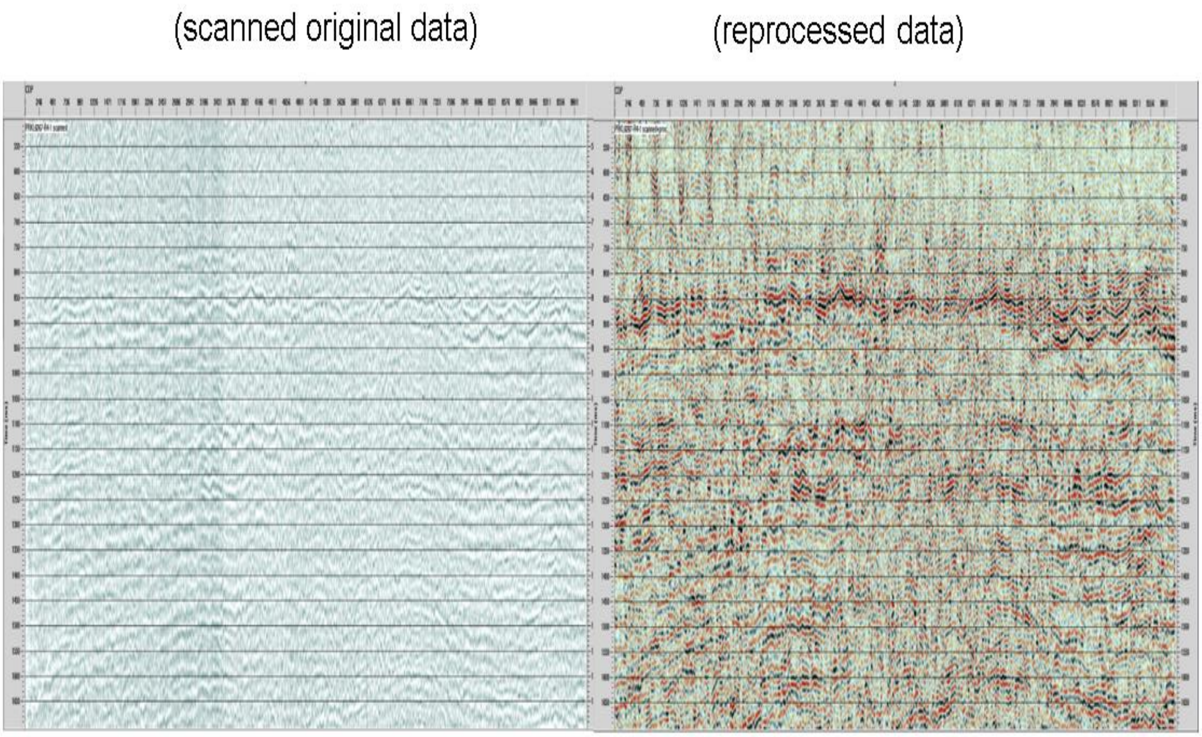
- *Source*: Seismic
- *Reference instance*: Stenlille 3D (zero shift)
- *Property-1*: Vertical shift between window -700 to 1800 ms TWT
- *Property-2*: Constant shift



	Use	Line/Cube	SP/ Plane	CDP/ Inline	Trace/ Xline	Vertical mis-tie	Correlation factor	Vertical correction	Vertical residual	Phase mis-tie	Correlation factor	Phase correction
76	☑	DN_94_D03	495	495	495	3.68	0.9025	15.36	-11.68			-0.0
77	☑	DN_94_D03	428	428	428	-4.02	0.8960	15.36	-19.38			-0.0
78	☑	DN_94_D03	593	593	593	0.59	0.8620	15.36	-14.76			-0.0
79	☑	DN_94_D03	406	406	406	0.67	0.8767	15.36	-14.69			-0.0
80	☑	stenlille3d_mig	Inline	1172	544	-38.39	0.8339	0.00	-38.39			-0.0
81	☑	stenlille3d_mig	Inline	1172	473	-14.51	0.8943	0.00	-14.51			-0.0
82	☑	stenlille3d_mig	Inline	1172	382	-15.04	0.9016	0.00	-15.04			-0.0
83	☑	stenlille3d_mig	Inline	1172	544	-23.82	0.8157	0.00	-23.82			-0.0
84	☑	stenlille3d_mig	Inline	1172	573	-11.33	0.8789	0.00	-11.33			-0.0
85	☑	stenlille3d_mig	Inline	1172	446	-16.88	0.8575	0.00	-16.88			-0.0
86	☑	stenlille3d_mig	Inline	1172	505	-34.77	0.8841	0.00	-34.77			-0.0
87	☑	stenlille3d_mig	Inline	1172	289	-17.83	0.8963	0.00	-17.83			-0.0
88	☑	stenlille3d_mig	Inline	1172	579	-14.08	0.8343	0.00	-14.08			-0.0
89	☑	stenlille3d_mig	Inline	1172	506	-12.97	0.8855	0.00	-12.97			-0.0
90	☑	stenlille3d_mig	Xline	1162	485	-9.34	0.8797	0.00	-9.34			-0.0
91	☑	stenlille3d_mig	Xline	1209	485	-12.89	0.8367	0.00	-12.89			-0.0
92	☑	DN_94_D02	71	71	71	8.30	0.8578	16.99	-8.69			-0.0
93	☑	DN_94_D02	263	263	263	7.90	0.9225	16.99	-9.09			-0.0
94	☑	DN_94_D02	391	391	391	-3.60	0.9269	16.99	-20.59			-0.0
95	☑	DN_94_D02	455	455	455	12.51	0.8943	16.99	-4.47			-0.0

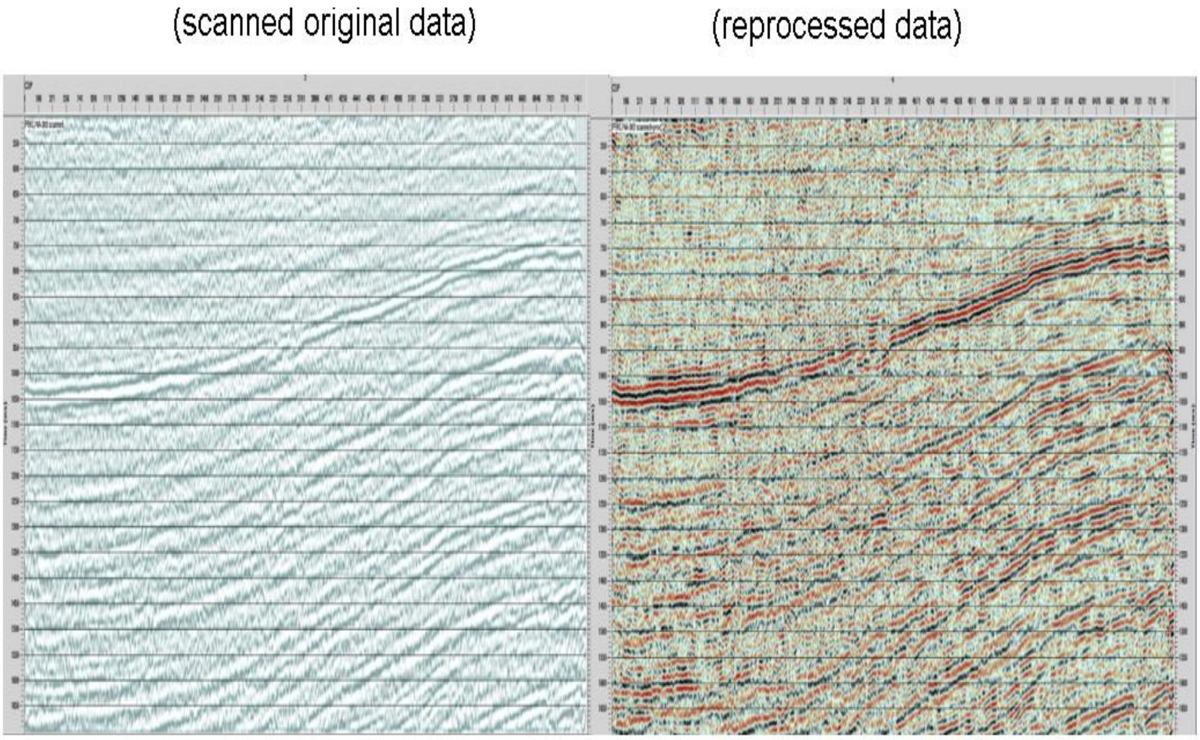
Appendix 1C. Example of mis-tie analysis (constant shift) between Stenlille-97 3D and the 2D surveys DN87O and DN94O.

Appendix 2(A) – Three reprocessed seismic sections



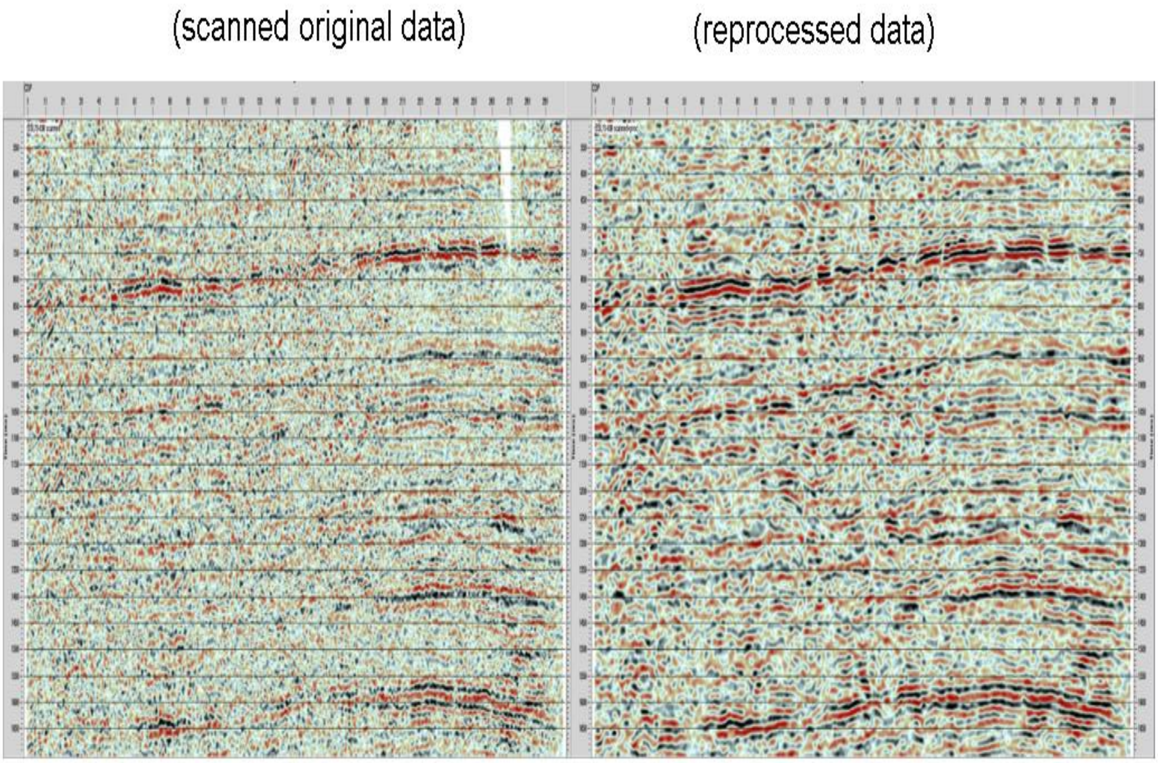
Appendix 2A. Reprocessed 2D seismic line R4_1 from the PRKL6267 survey (vertical scale in milliseconds TWT) from ProMAX. The figure shows the scanned original data of the project database and the reprocessed data. See also the line position and interpretation of the line in Figure 9.

Appendix 2(B) – Three reprocessed seismic sections



Appendix 2B. Reprocessed 2D seismic line 74_303 from the PRKL74A survey (vertical scale in milliseconds TWT) from ProMAX. The figure shows the scanned original data of the project database and the reprocessed data. See also the line position and interpretation of the line in Figure 9.

Appendix 2(C) – Three reprocessed seismic sections



Appendix 2C. Reprocessed 2D seismic line SSL73_038 from the SSL7273 survey (vertical scale in milliseconds TWT) from ProMAX. The figure shows the scanned original data of the project database and the reprocessed data. See also the line position and interpretation of the line in Figure 9.