DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/34**

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)

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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 CO2 capture technologies, (2) the potentials for both temporary and permanent storage of CO2 in the Danish subsurface, (3) mapping of transport options between point sources and usage locations or storage sites, and (4) the CO2 usage potentials, including business case for converting CO2 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 6 and focuses on a seismic interpretation of existing 3D seismic data around the Stenlille structure within the framework of sequence stratigraphy and with focus on the Gassum Formation.

Content

Dansk sammendrag

Denne undersøgelse omfatter en seismisk tolkning og kortlægning af sekvensstratigrafiske horisonter i Gassum Formationen baseret på et 3D seismisk datasæt, der dækker størstedelen af Stenlille strukturen. Sedimentologiske og palynologiske data er integreret i tolkningen og indgår i opstillingen af en overordnet geologisk model for Gassum Formationen. Med udgangspunkt i modellen redegøres der for vigtige input til opstilling af reservoirmodeller for Gassum Formationen i Havnsø strukturen.

Sekvensstratigrafisk dækker Gassum Formationen i Stenlille over syv sekvenser (SQ1–SQ7). I sin nedre del afspejler formationen et overordnet fremadrykkende aflejringssystem (afspejlet ved at kysten ved hver efterfølgende sekvens rykkede længere ud i bassinet) efterfulgt af et overordnet tilbagerykkende aflejringssystem (afspejlet ved at kysten ved hver efterfølgende sekvens rykkede længere ind mod bassinets rand). I Havnsø strukturen forekommer de tykkeste og største koncentrationer af sandsten sandsynligvis under den transgressive flade TS5, der adskiller det underliggende fremadrykkende system fra det overliggende tilbagerykkende system.

Til dannelsen af sekvensgrænsen SB5 knytter sig en betydelig erosion med transport af eroderede sedimenter ud i bassinet til følge. Dette har sandsynligvis bidraget til aflejringen af sand i området, hvor Havnsø strukturen er beliggende - sand der i dag kan udgøre et vigtigt reservoir. Gassum Formationens sandsten i Havnsø strukturen vurderes i høj grad til at være sammenlignelige med formationens sandsten i Stenlille strukturen. Dette understreger relevansen af at anvende Stenlille data til analogstudier, eksempelvis kernemateriale fra Stenlille boringerne til at vurdere porøsitet- og permeabiltetsværdier og den diagenetiske sammensæt af sandsten i Havnsø strukturen.

Summary

This study presents a seismic interpretation and mapping of key sequence stratigraphic horizons of the Gassum Formation based on a 3D seismic survey covering the main part of the Stenlille structure. Data on sedimentology and palynology are integrated in the interpretation and an overall geological model for the Gassum Formation is presented as is important sedimentological inputs, extracted from the Stenlille data, for setting up reservoir models for the Gassum Formation in the Havnsø structure.

The Gassum Formation covers seven sequences (SQ1–SQ7) of which the stratigraphic lowermost sequences (SQ1 to the transgressive surface TS5 of SQ5) reflect an overall progradational development with sequences 1–3 consisting mainly of offshore to shoreface deposits followed by sequences 4 and 5 which also contain thick intervals of fluvial-deltaic and fluvial-estuarine sandstones. Above TS5, offshore to shoreface deposits dominate with the backstepping pattern culminating with the deposition of offshore mudstones of the Fjerritslev Formation.

The thickest and highest concentration of reservoir sandstone intervals in the Havnsø structure most likely occur below TS5. These sandstones are probably very similar to those in the Stenlille structure and some of them may even extend over both structures. Significant erosion and basinwards bypass of sediments is associated with the formation of SB5 and has probably contributed to the deposition of sand in the Havnsø structure. This emphasize the relevance of the reservoir sandstones of the Gassum Formation in the Stenlille structure as analogues for sandstones in the Havnsø structure, e.g. for giving estimates on reservoir properties of sandstones in the Havnsø structure such as poro-perm and diagenesis analysis based on Stenlille data.

Introduction

For the estimation of the storage potential of CO_2 in the Havnsø structure, the geological setting at Stenlille is assumed to represent the best possible analogue since similar lithologies and burial depths for the Gassum Formation is expected as well as the structural development seems similar. The Stenlille structure is situated c. 30 km southeast of the Havnsø structure and has the most comprehensive onshore dataset in Denmark, including some 2D seismic lines, a 3D seismic survey from 1997 and a total of 20 injection, production and observation wells (Fig. 1). Since the 90's, natural gas has been injected into and stored in sandstones of the Gassum Formation which occurs within a domal closure and is overlain by seal-forming mudstones of the Fjerritslev Formation. In Stenlille, the Gassum Formation is approximately 140 m thick with its top occurring around 1470–1600 m below ground surface. DONG defined six reservoir/seal zones in the Gassum Formation but only the upper 40 m of the formation, covering Zones 1–4 and the upper part of Zone 5, is used for gas storage in order to prevent gas migration through the spill-point (Fig. 2).

This report deals with a seismic facies study of the Gassum Formation in the Stenlille structure based on the existing 3D seismic survey. A sequence stratigraphic subdivision of the Gassum Formation and the basal part of the Fjerritslev Formation in the Stenlille wells is shown in Hovikoski & Pedersen (2020). The subdivision is based on an interpretation of depositional environments and identification of important facies shifts based on comprehensive core-descriptions, palynofacies analyses and interpretation of log-pattern motifs. In the present study, an attempt has been made to map out those of the sequence stratigraphic surfaces, which are identifiable in the 3D seismic dataset, thereby revealing the extent and lateral thickness variations of the depositional packages bounded by the sequence stratigraphic surfaces. Together with the interpretation of depositional environments, this is an important input to set up reservoir-models for the Gassum Formation in the Havnsø structure when the geological model of Stenlille is used as an analogue (e.g. to estimate extent, thickness and orientations of internal sandstone reservoir intervals).

Database

The 3D seismic survey at Stenlille, acquired in 1997, covers approximately 56.4 km^2 of 16-fold data (Fig. 3). However, the dataset has several limitations as it contains substantial noise related to ground-roll noise etc. as outlined in Bredesen (submitted). Distance between the seismic lines is c. 20 m. In general, a seismic interpretation has been made for every 5–10 InLine and XLine.

All wells occur within the 3D seimic survey area except Stenlille-6 which is situated nearly 1 km NE of the north-eastern limit of the survey area (Fig. 3). The wells occur close to the top of the domal structure within the survey area except for the Stenlille-4, -5, -10 and -15 wells, which have more down-dip positions on the structure. Unfortunately, Stenlille-19 is the only Stenlille well which is considered to correlate correctly with the seismic reflectors (Fig. 4). In contrast to the other Stenlille wells, a comprehensive well data set is available from this well with many log types, Vs, Vp and check-shots, providing a valid time-depth(m) relation. The data are used for synthetic seismograms and seismic to well tie (see also Gregersen et al. 2020, Bredesen 2020). For all the other wells it has not been possible at present to come up with a common time-depth(m) correlation which depth wise places them correctly relatively to the seismic data at the level of the Gassum Formation. The database was provided for this study in a workstation project with Petrel © software (version 2017.4).

Presentation of seismic horizons, seismic time-structure and -thickness maps

In Figures 5–9, seismic time-structure maps (below terrain surface) and time-thickness maps (in milliseconds two-way travel time – ms TWT) are shown for the Gassum and Fjerritslev formations based on the interpretation of the 3D seismic dataset. The maps of Base Gassum, Top Gassum, Top Fjerritslev and faults are from Gregersen et al. (2020), whereas maps of sequences are all from the present study.

On the seismic time-structure maps, the salt doming structure is clearly seen in the area where most of the Stenlille wells are concentrated. The top-point of the structure occurs at c. 970 ms TWT and c. 765 ms TWT at the Top Gassum and Top Fjerritslev levels, respectively (Figs. 6 and 8). The faults zones shown on the Top Gassum and Top Fjerritslev maps are interpreted as being mainly of post-Fjerritslev Fm and pre-Chalk Group age as outlined in Gregersen et al. (2020). From the time-thickness maps it is evident that Gassum Formation is up to around 90 ms TWT thick within the survey area and Fjerritslev Formation, forming the seal for the Gassum reservoir, is up to around 245 ms TWT thick, decreasing to around 200 ms TWT in the area of the top-point of the structure (Figs. 7 and 9).The thinning of the Fjerritslev Formation towards the structural top-point is due to erosion at its top and suggests that salt doming had taken place in “Top Fjerritslev time” (Gregersen et al. 2020). The erosional surface most likely represents the base mid-Jurassic unconformity (mid-Cimmerian unconformity). It is onlapped by a thin succession including the Vedsted Formation and the structure is topped by the Chalk Group (Gregersen et al. 2020).

In this study, focus is on the depositional setting of the Gassum Formation, which contains the most obvious sandstone intervals for CO_2 storage. The outcome of the 3D seimic mapping (including seismic time-structure maps, time-thickness maps and examples of seismic sections) is presented within the framework of a sequence stratigraphic subdivision of the Gassum Formation. Focus is thus not entirely on the 3D seismic data but also incorporate data on sedimentology, palynology and sequence stratigraphy reported within the CCUS project (Hovikoski & Pedersen 2020 and Lindstrom 2020) and in previous studies (e.g. Hamberg & Nielsen 2000). Subsequently, an overall geological model for the Stenlille area is outlined and important input to consider, when reservoir models for the Havnsø structure are constructed, is also presented. In these considerations, the possibility that the Havnsø area most likely represents a more distal basinal position compared to the Stenlille area in “Gassum time” (Fig. 10), must be included.

The sequence stratigraphic subdivision of the Gassum Formation in many of the Stenlille wells is shown in a log-correlation panel in Hovikoski & Pedersen (2020) and is based mainly on interpretation of well data (mainly sedimentological core descriptions, vertical gamma-ray log motifs and biostratigraphic analysis). In Figures 11 and 12 the sequence stratigraphic subdivision of the Stenlille-1 and Stenlille-19 wells are shown. As mentioned above, it is only the Stenlille-19 well which is considered to correlate correctly with the seismic reflectors (Fig. 4). Consequently, the mapping of seismic reflectors, interpreted to represent sequence stratigraphic surfaces, relies almost entirely on the Stenlille-19 well.

The resolution of the seismic data is not high enough to reveal all of the sequence stratigraphic surfaces identified based on well data. Thus, as outlined in Figure 11, only the following sequence stratigraphic surfaces, listed in ascending order (stratigraphic lowest to the highest), are mapped: MFS2, SB3, MFS3, SB4, MFS4, SB5, TS5, SB6 and TS9. The transgressive surface TS9 in fact occurs within the Fjerritslev Formation, topping a basal part of the formation that is sandier than the remaining part of the formation which is largely dominated by mudstone. Furthermore, the Top Gassum horizon corresponds approximately to the transgressive surface TS7. The numbering of sequences and their associated surfaces follows the sequence stratigraphic nomenclature given in Nielsen (2003).

The horizons are not equally easy to map and in general the uncertainty in mapping and assigning reflectors to the sequences stratigraphic surfaces increases with increasing distance to the Stenlille-19 well. Sequence boundaries which in some wells occur at the top of coarsening-upwards sandstone units are in other wells present at the base of fining-upwards sandstone units (representing channel incision at falling relative sea-level and succeeding infill during base level rise). This makes it difficult to map out such sequence boundaries on the seismic data as it is generally not possible to deduce where these position shifts take place. Consequently, the mapped sequence boundaries may show small jumps on the seismic sections as is especially the case for sequence boundary SB6.

In some intervals of the Gassum Formation, sequences of different orders seem to be present and the resolution of the seismic data are commonly not good enough to distinguish these from each other thereby making the mapping of individual sequences a difficult task. Also, the resolution does generally not allow the identification of systems tract sensu Hunt & Tucker (1993) and Catuneanu et al. (2009); e.g. to distinguish between highstand systems tracts (HST) and falling stage systems tracts (FSST). Thus, only sequence boundaries (SB) and maximum flooding surfaces (MFS) and in some cases transgressive surfaces (TS) are identified on the seismic data.

Nether the less, the seismic data, integrated with data on depositional environments, reveals important hints about the overall depositional setting in the Stenlille area as well as possible periods of sand supply from the area to the more basinwards position, which the area of the Havnsø structure is interpreted to represent at the time the sediments of the Gassum Formation were deposited (Fig. 10).

In the following, the seven sequences (SQ 1–7) which cover the Gassum Formation in the Stenlille area are presented. Data on depositional environments given in Hovikoski & Pedersen (2020) and Lindström (2020) are incorporated and the outcome of the seismic mapping is illustrated with mapped horizons marked on seismic sections and constructed seismic time-structure maps and time-thickness maps between selected surfaces (all maps shown in milliseconds two-way-travel time). All the seismic sections are shown in TWT (two-way travel time in milliseconds) and with a vertical exaggeration of 10. In those sections which pass through the Stenlille-19 well, the position of the well is marked on the sections by a black vertical stippled line and next to this its gamma-ray log motif is seen. For those sections, which pass through or close to other Stenlille wells, a vertical stippled line only marks the position of the wells, as the associated gamma-ray logs are not located correctly relatively to the seismic reflectors. In the construction of time-structural and time-thickness maps, a grid cell size of 50x50 m was used. The mapped faults of Gregersen et al. (2020), shown on the Top Gassum and Top Fjerritslev time-structural maps in Figures 6 and 8, respectively, are not marked on the seismic sections, nor are they incorporated in the construction of the presented time-structural and time-thickness maps. In those areas, where major faults are present, more abrupt time-depth variations across the overall NE–SW striking faults are thus expected than revealed on the present time-structural maps. Faulting is interpreted as having taken place approximately at the time of formation of the Top Fjerritslev Fm and before the Chalk Group was deposited over/across the top of the structure (Gregersen et al. 2020).

Sequences 1 and 2

The basal part of the Gassum Formation is represented by the HST of SQ1 and the overlying sequence 2. The basal part of the of SQ1 belongs to the Vinding Formation which is interpreted to comprise shallow and restricted marine deposits (Bertelsen 1978, Nielsen 2003). The HST of SQ1 consists of a coarsening-upwards sandstone unit, reflected by an upwards decreasing gamma-ray log motif (Fig. 12). SQ2 consists of an upwards-fining sandstone unit topped by the MFS occurring in a thin mudstone interval represented by a gamma-ray peak. Above this is a relatively thin coarsening-upwards HST is present (Fig. 12).

Data from this basal part of the Gassum Formation are sparse as it has not been cored. A single palynofacies analysis on a cuttings sample from the HST of Sequence 1 suggests a marginal marine depositional environment (Lindström 2020). On the seismic data it has only been possible to identify Base Gassum and MFS2 (Fig. 11). Seismic time-structure maps (ms TWT) of these are shown in Figures 5 and 13, respectively. A time-thickness map of the Gassum Formation below SB3 reveals that the interval covered by the HST of SQ1 and SQ2 has a relatively uniform thickness of 6–16 ms TWT within the 3D survey area (Fig. 14). Overall, it appears that the interval is slightly thicker within the north-eastern part of the 3D survey area compared to the south-western area, which possibly reflects shoreface progradation from the NE into the area.

Based on the overall setting revealed by the overlying sequences (see below), the interval is interpreted to represent overall offshore–shoreface deposition within a restricted environment, e.g. an embayment.

Sequence 3

On gamma-ray logs of the Stenlille wells the basal sequence boundary, SB3, is generally seen as a marked fall in the gamma-ray log motif reflecting an abrupt shift from offshore mudstones of the underlying SQ2 to the deposition of sandstones (Fig. 12). An aggradational to slightly fining-upwards interval of sandstones overlies SB3, probably representing the LST of the sequence. Hamberg & Nielsen (2000) interpreted these sandstones as being shoreface deposits. The sandstones are overlain by a mudstone-dominated interval which contains the maximum flooding surface (MFS3 in Fig. 12) and which is interpreted to represent offshore deposition (Hamberg & Nielsen 2000). However, in some wells the offshore mudstones are absent; making it difficult to localize the MFS as aggradational to progradational sandstones of the highstand systems tract directly overlies the sandstones of the LST. The sandy HST is relatively thin and is interpreted to represent progradational shoreface deposits (Hamberg & Nielsen 2000). The sequence is especially thick, up to around 50 m, in the Stenlille-15 well where it consists of mudstone and subordinate sandstone intervals (Figs. 15 and 16).

The sequence has not been cored. Palynofacies analysis on cuttings samples from the Stenlille-4 and Stenlille-6 wells indicate marginal marine or marginal marine to shallow marine depositional conditions (Lindström 2020). Analysis on cutting samples from the Stenlille-15 well, where the sequence is considerably thicker than in the remaining wells, reflect fluctuation between marginal marine, shallow marine and terrestrial depositional environments. This suggests that the overall offshore–shoreface depositional setting, suggested by Hamberg & Nielsen (2000), did not occur in an open-marine setting but merely within a more restricted basinal setting such as an embayment. The blocky gamma-ray log motif of the sandstone interval in the lower part of the sequence show affinities to the gamma-ray log motifs of the basal sandstone intervals in Sequences 4 and 5 which among others are interpreted to reflect fluvial-deltaic and fluvial-estuarine deposition based on sedimentological core analysis and palynofacies analysis (see below). It may be that the basal LST sandstones in Sequence 3 also represent such depositional environment but more palyno samples are needed from this interval to deduce if this is the case.

A seismic time-structure map (ms TWT) of SB3 is shown in Figure 17 and a time-thickness map of the sequence below MFS3 is seen in Figure 18. The latter reveals that the LST (and subordinate the TST) of the sequence is especially thick in the western and south-western area of the survey. The time-thickness pattern of the map may suggest LST progradation into the area from a western to southwestern source area and perhaps also a minor sediment input from the east as suggested by the slightly thickness increase seen in the eastern corner of the survey area. Progradation into the area from the W-SW is supported by one of the seismic sections on which SB3 shows truncation into SQ2 and reflectors above SB3 are dipping towards the NE (Fig. 19).

Sequence 4

This sequence is cored, e.g. in the Stenlille-18 well, and sedimentological interpretations of the cores gives valuable information on the depositional environments the sequence represent as outlined in Hovikoski & Pedersen (2020) (Fig. 20). The sequence commences with a thick, aggradational sandstone interval, up to around 35 m thick, which probably represents the LST of the sequence. The sandstones form a large part of DONG´s reservoir zone 6 (Fig. 12) and are interpreted to reflect fluvial-deltaic and fluvial-estuarine deposition in an environment where sediment supply generally was able to keep up with repeatedly generated accommodation space for deposition (Hovikoski & Pedersen 2020). The transgressive systems tract, commencing with TS4, is characterized by a back-stepping gamma-ray log motif and reflects a transition to deposition of mud and sand within a lagoonal complex (Hovikoski & Pedersen 2020). These deposits contain the MFS, which correlates to a marked gamma-ray peak (Fig. 12). The HST is thin and consists likewise of lagoonal deposits. In the Stenlille-15 well, signs of the development of palaeosoils above TS4 indicate a more terrestrial influenced environment (e.g. backshore) than in the remaining wells where the lagoonal deposits dominate the interval above TS4 (Hovikoski & Pedersen 2020, Lindström 2020).

A time-structural map of SB4 and a time-thickness map of SQ4 are shown in Figures 21 and 22, respectively. From the maps it is evident that the sequence does not cover the whole 3D survey area. Seimic XLine sections suggest that the sequence actually represents two episodes of depositional progradation (Fig. 23), perhaps formed by separate high-order relative sea-level fall and if so, in fact represent separate sequences. On the time-thickness map, the extent of the first progradational event ("SQ4a") is represented by the mapped area furthest to the south-east which is relative small but probably extend beyond the 3D survey area further to the SE. Deposits of the second progradational event ("SQ4b") has a much larger extent within the 3D survey area than the deposits of the first progradational event and probably extend beyond the survey area along a part of the north-western borderline of the survey (Figs. 21 and 22). Locally, internal seismic reflectors, most likely assigned to the LST, are dipping towards the NW (Fig. 23).

Originally the extent of Sequence 4 was probably larger within the survey area as the seismic sections reveal, that the delimitation of the sequence is mainly caused by erosion related to the formation of the overlying SB5 (see description of Sequence 5 below). However, in some InLine sections, Sequence 3 also appears to wedge out towards SW in contrast to the northern and northeastern part of the survey area where the seismic sections reveal marked truncation. All of the Stenlille wells present within the survey area contains deposits of the second progradational event, including the thick LST interval of fluvial-dominated sandstones. The exception is the Stenlille-15 well, which is located near the southwestern areal limit of the sequence (Figs. 3 and 22) and in which only the uppermost part of sequence 4, dominated by terrestrial mudstone and sandstone deposits, seems to be present.

The deposits of SQ4 are interpreted to reflect overall fluvial-deltaic progradation from the SE based on the outlined areal extent of the sequence and local evidence of internal seismic reflectors dipping towards the NW (Fig. 23). This fits well with zircon ages of a sandstone sample from the fluvial-dominated LST of the sequence, which indicate sediment input from a southern or south-eastern source area, probably from the eastern parts of the Ringkøbing–Fyn-High (Olivarius, pers. comm., see below).

Sequence 5

This sequence is cored in several Stenlille wells, and sedimentological interpretations of the cores gives valuable information on the depositional environments the sequence represents as outlined in Hovikoski & Pedersen (2020). On gamma-ray logs of the Stenlille wells, the basal sequence boundary, SB5, is generally seen as a marked fall in the gamma-ray log motif reflecting an abrupt shift from lagoonal mudstones of the underlying SQ4 to an up to around 40 m thick sandstone succession, corresponding to DONG´s reservoir zone 5, which is characterized by an aggradational gamma-ray log motif or in some wells an interval of several slightly fining-upwards motifs (Fig. 12). The sandstone interval represents the LST of the sequence and is interpreted to represent fluvial-deltaic, fluvial-estuarine as well as shoreface deposition in an environment where sediment supply was able to keep up with repeatedly generated accommodation space for deposition (Hovikoski & Pedersen 2020) (Fig. 20). In its uppermost part, the sandstone succession may locally show a shift to a back-shore depositional setting (Fig. 20). The sandstone succession is topped by TS5 above which follows muddy lagoonal deposits overlain by offshore–lower shoreface intercalated mud-stone and sandstone in some wells whereas in other wells deposits of the latter follows directly above TS5. The maximum flooding surface, MFS5, correlates to a marked gamma-ray peak within the offshore mudstone interval. The HST is relatively thin, in a few wells nearly absent (e.g. in Stenlille-1 in Fig. 12) and is on gamma-ray logs reflected by an upwards de-creasing motif representing progradational offshore–shoreface deposits as outlined in Hovikoski & Pedersen (2020).

In some seismic sections, reflectors are seen to extend downwards from the overlying SB6 and pinch out towards NW (Fig. 24). These may represent falling stage systems tract deposits, recording stepwise shoreline progradation towards the W or NW under a general low-order sea-level fall moderated by higher-frequency oscillations of relative sea level as outlined in the paper of Hamberg & Nielsen (2000). The low-order fall thus resulted in wide-spread progradation, in the end leading to the formation of SB6, whereas the high-order oscillation (superimposed on the low-order fall) led to the formation of high-order sequences consisting of seaward-dipping, shingled depositional units, represented by the above men-tioned reflectors “pinching-out” towards the NW.

A time-structural map of SB5 is seen in Figure 25 and a time-thickness map of the sequence below TS5 (corresponding to the LST of the sequence) is seen in Figure 26. The time-thickness map reveals that large thicknesses especially occur in two areas, 1) in the southern corner of the survey area from where the thickness decreases gradually towards the NW and more markedly in northern directions, and 2) in the northern corner area and in a zone down along a part of the north-western border of the survey area. Seismic sections crossing the first-mentioned area show NW-directed downlap onto the SB5 horizon (Fig. 27), indicating LST progradation in this direction. Seismic sections crossing the latter area, show marked truncation at the base of the sequence and above SB5 subtle reflectors dipping towards NW are seen, suggesting LST progradation in this direction (Fig. 23).

SB5 truncating into underlying deposits is seen at several places on the seismic sections. A rough mapping of where truncation is observed on the seismic sections is seen on the map in Figure 28. The erosional pattern seen in the western area on the map shows some similarities with likely channels revealed on amplitude maps constructed for time-depth slices of around 1050 ms TWT. As an example of this, a time-depth slice map of 1048 ms TWT, is shown in Figure 29, revealing the presence of channels within the western area of the 3D survey. Such amplitude maps should be interpreted with caution as the domal occurrence of the Gassum Formation implies that time-slice maps as the one shown in Figure 29 may represent very different stratigraphic intervals of the Gassum Formation when moving laterally on the map. However, at least for the western area, time depths around 1050 ms TWT appears to be in accordance with the time depths in which truncation by SB5 has been observed on seismic sections crossing the area.

It is striking that the areas where SB5 shows marked truncation seems to encircle a non-truncated central part of the domal structure (Fig. 28). This might be interpreted as reflecting initial salt doming in this area following the deposition of SQ4. An incipient doming may have caused rivers, following the topographic lowest-lying parts in a landscape, to erode mainly along the flanks of the possibly slightly developed domal structure. Towards NE the removal of SQ4 deposits, related to the formation of the SB5, is evident in a broad zone along the north-eastern border of the 3D survey and it seems likely that the removal extend further towards NE, beyond the survey area. However, SQ4 is present in the Stenlille-6 well located nearly 1 km NE of the 3D survey area. This suggests that the surface of SB5 forms a depression, possibly an incised valley somewhere between the Stenlille-6 well and where it incises into SQ4 within the north-eastern part of the 3D survey area. The marked erosion of SQ4 deposits at the time SB5 was formed, suggests basinwards transportation of eroded sediments with possible deposition in the Havnsø structure area.

Sequence 5 thus reflects considerably erosion at its base, perhaps taking place after a weak domal uplift within the survey area prior to the main uplift taking place approximately at the time of formation of the Top Fjerritslev Fm as mentioned above. The erosional event was succeeded by overall fluvial-deltaic, fluvial-estuarine and shoreface LST deposition showing progradation into the area from the SE. Rising relative sea level eventually led to a drowning of the fluvial depositional systems, and subsequently deposition of shoreface sand and offshore mud took over.

Sequence 6

The sequence occurs in the upper part of the Gassum Formation and covers DONG´s reservoirs zones 2a–2b and partly zone 3 (Fig. 12). In most wells, SB6 occurs at the top of a coarsening-upwards shoreface unit of the underlying SQ5 and is overlain by fluvial-deltaic LST deposits or locally backshore or lagoonal deposits (Hovikoski & Pedersen 2020). In places, the fluvial-deltaic deposits form fining-upwards units, up to nearly 20 m thick, probably reflecting deposition within deep channels or possibly incised valleys (e.g. in the Stenlille-1 and Stenlille-19 wells). In all wells, a marine drowning is reflected by the presence of offshore to lower shoreface mudstone and sandstone deposits forming the upper part of the sequence (Fig. 20). Sedimentological core analysis generally places the maximum flooding surface (MFS 6) at a gamma-ray peak close to the top of the sequence implying that the HST of muddy deposits is very thin (Fig. 12).

As mentioned in the introduction to this chapter, it is very difficult to map out on the seismic data where SB6 change position from occurring at the top of coarsening-upwards sandstone units (representing the HST of Sequence 5) to where it occurs at the base of fining-upwards sandstone units. The apparent occurrence of higher-order sequences, extending downwards from SB6 and representing the falling stage systems tract of SQ5, further complicate a precise mapping of SB6.

A time-structural map of SB6 is seen in Figure 30 and a time-thickness map covering the SB6–Top Gassum interval is seen in Figure 31. Apart from SQ6, the thickness map includes the main part of SQ7 (up to TS7) as it has not been possible to map SQ7 as a separate sequence on the seismic data. However, well data indicate that the thicknesses revealed by the time-thickness map shall mainly be assigned to SQ6. By comparing the time-thickness map with that of SQ5 (Fig. 26), it is striking that thicknesses are very low in those areas where SQ5 is especially thick (areas pointed out in the description of SQ5 above). In the southernmost corner, where SQ5 is exceptionally thick, SQ6–SQ7 deposits are even lacking (or are below seismic resolution), suggesting that this may have been an area of sediment bypass or non-deposition at the time the sequences were formed (see also Fig. 27 for an example of a seismic XLine section crossing this area).

In addition, it is striking that the SQ6–SQ7 deposits are relatively thin in the central part of the domal structure. In contrast, the interval is thick in an overall SE–NW striking zone parallel with the zone of low thickness to the far SW (Fig. 31). This perhaps reflects accommodation space for deposition mainly being present in a topographic depression between a topographic high-lying area to the SW (consisting of thick deposits of SQ5) and a slightly elevated North-eastern part of the survey area caused by initial salt doming as discussed above in the description and interpretation of SQ5. Thus, although SB6 has a broad shallow channel appearance on SW–NE orientated InLine sections crossing the area of thick deposits (Fig. 19) this does not necessary reflect deep valley incision and succeeding infill but merely the infilling of an existing relief. However, channel incision and possible bypass of sediments towards the Havnsø structure did most likely occur in places, as documented by the presence of fining-upwards sandstone units in the Stenlille-1 and Stenlille-15 wells at the base of the sequence, interpreted as representing mainly fluvial-deltaic infill of channels.

It is difficult to point out internal dipping reflectors within SQ6, which with certainty reveal directions of overall progradation. However, due to the close association to the underlying falling stage systems tract of SQ5, consisting of seaward-dipping, shingled depositional units recording stepwise shoreline progradation towards the W or NW under the general sea-level fall which led to the formation of SB6, it appears likely that progradational deposits within SQ6 also reflect progradation in these directions. The sequence reflects an overall retrogradational depositional pattern with fluvial-deltaic or locally lagoonal sediments above the sequence boundary, followed by the deposition of offshore to lower shoreface sediments forming the upper part of the sequence. Hamberg & Nielsen (2000) interpreted sandy lowstand deposits of the sequence to cover the eastern part of the Danish Basin, including the Havnsø structure area, during maximum progradation (Fig. 10A).

Sequence 7

The sequence is relative thin. In most of the wells the lower part of the sequence consists of two sandstone intervals, separated by a muddy heterolithic interval, in general representing deposition within the offshore–shoreface zone. SB7 is generally placed at base of the lowest sandstone interval based on core observations (Hovikoski & Pedersen 2020) (Fig. 20). The uppermost sandstone unit is topped by the transgressive surface TS7, which corresponds to the top of the Gassum Formation. Above this follows offshore mudstones of the Fjerritslev Formation constituting the remaining part of the sequence and comprising MFS7. In the Stenlille-6 well, the sequence stands out from elsewhere by also containing tidal flat deposits and by showing an overall fining-upwards gamma-ray log motif with the upper part representing a relative thick succession of offshore heteroliths (Hovikoski & Pedersen 2020).

The resolution of the seismic data is too low to map SB7 and the overlying SB8 and it is thus not possible to construct time-thickness maps of the sequence. As mentioned above, the SB7–top Gassum (TS7) interval forms part of the time-thickness map which also include SQ6 (Fig. 31). But as pointed out by Bredesen (submitted), even the top Gassum reflection can be somewhat challenging to interpret due to interfering reflection events from the overburden of the Fjerritslev Formation which up to TS-9 is composed of heterogeneous, alternating layers of mudstone and sandstones.

Hamberg & Nielsen (2000) interpreted the base of the sandstones to represent a forced regressive surface and the sandstones above as LST deposits. Furthermore, they interpreted the deposits as reflecting deposition towards the SW, thus reflecting a shift in the direction of progradation compared to the underlying sequences which mainly reflect progradation in western-northwestern directions. They did not consider LST sand of the sequence to have reached the Havnsø structure area during maximum progradation (Fig. 10B). However, the fact that the deposits of the sequence is more fine-grained in the Stenlille-6 well than in the remaining Stenlille wells do not seem to fit well with depositional progradation from NE towards SW as this well then should represent a more proximal position compared to the other wells (se well locations in Fig. 3). Furthermore, zircon ages of a sandstone sample from the sequence indicate sediment input from a southern or south-eastern source area (Olivarius, pers. comm., see below). Based on this, the sand of the sequence is here interpreted as representing shoreface progradation from the S-SE into the Stenlille area.

Overall geological model for Stenlille and input to reservoir models for the Havnsø structure

The seven sequences covering the Gassum Formation in the Stenlille area reflect overall progradation from the base of the Gassum Formation and up to TS5 whereas the sequences above this surface form an overall backstepping pattern. The progradational pattern is reflected by the transition from mainly offshore to shoreface deposition in sequences 1–3 being followed by sequences 4 and 5, which also contain thick, fluvial-deltaic and fluvial-estuarine dominated LST deposits. Above TS5, fluvial deposition ceases, with the exception of the fluvial-deltaic LST deposits of Sequence 6, and offshore to shoreface deposits dominate. The backstepping pattern culminates with the deposition of offshore mudstones of the Fjerritslev Formation although the basal part of this formation, up TS9, also contains relative thick intervals of sandy shoreface deposits. Palynofacies analysis from marine deposits below TS5 in general indicate marginal marine to shallow marine depositional environments, suggesting deposition in a restricted sub-basin, e.g. an embayment (Lindström 2020). Palynological evidence of marginal environments is also seen in marine deposits above TS5 but in general palynofacies indicate shallow marine or fully marine conditions, thus reflecting the overall backstepping of the coastline towards the basin margins and accordingly stepwise enlargement of sea-covered areas.

Thick sandstone intervals within the Gassum Formation in most cases represent fluvial-dominated lowstand deposits. For many of the sequences, the highstand systems tract is relatively thin compared to the remaining part of the sequence. This might reflect that rise in relative sea level caused considerably coastal withdrawal which is likely to occur in low-gradient basin floor settings. Progradation and significant deposition in the Stenlille area then returned in periods of relative sea-level fall.

As mentioned above, SB6 and the underlying falling stage systems tract deposits of SQ5 are interpreted to reflect an overall relative sea-level fall under which higher-frequency oscillations of relative sea level led to the formation of seaward-dipping, shingled depositional units (represented by the FSST deposits of SQ5). It can be speculated if similar conditions prevailed during the formation of SQ4 and SB5. SQ4 reflects two episodes of progradation towards the NW. The second of these is on seismic sections seen to extend downwards from SB5 in its proximal part whereas only the distal “out-pinching” reflector of the first progradational event is revealed within the 3D survey area (Fig. 23). The two progradational episodes of SQ4 may in fact represent higher-order relative sea-level oscillations relatively to (and during) a long-lasting overall relative sea-level fall which led to the formation of SB5 (as outlined in Fig. 32).

The most intensive erosional event, and possible associated bypass to the Havnsø structure area, relates to the formation of SB5. This sequence boundary thus shows a marked erosional relief and in places the erosional event has resulted in a complete removal of the deposits of Sequence 4, e.g. in the North-eastern part of the 3D survey area. It seems likely that bypassed sediments from this erosional event were deposited basinwards as falling stage and lowstand deposits in the Havnsø structure area. Marked erosion in places also relates to SB6 and locally also SB3 but overall, these erosional events were less pronounced than for SB5. Incipient salt doming may have occurred after the deposition of SQ4 based on among others roughly mapped channel-like structures (associated to SB5), which appear to encircle a non-truncated central part of the domal structure over which SQ5 and SQ6 furthermore, are relative thin.

Direction of depositional progradation seems to have changed during the period the sediments of the Gassum Formation were deposited. Thus, the thickest sequences, SQ4–SQ6, and SQ7 indicate westerly to north-westerly progradation directions whereas SQ1–2 indicate progradation directions towards SW and SQ3 towards E-NE and subordinate towards W. Progradation directions towards SW suggest a Fennoscandian source area in the hinterland. In contrast, the northerly to westerly progradation directions suggest the Ringkøbing–Fyn High as a source area or possibly source areas south of this from where sediments may have been transported northwards through corridors intersecting the high. Two zircon age datings from the Gassum Formation in the Stenlille-wells (from sandstones of Sequences 4 and 7) indicate influx of sediments to the area from a southern or south-eastern source area. The ages thus indicate a southern provenance component in the sediments, most likely originating from reworking of the Bunter Sandstone Formation carrying zircons from the Variscan Oregeny (Olivarius, pers. comm.). The Skurup High Platform, on which Cretaceous deposits in places rest on basement, has been suggested as a possible source area and/or by-pass area for sands eroded from the Variscan Oregon, as the Bunter Sandstone Formation was not, or only to a very limited extent, exposed for erosion in the central parts of the Ringkøbing–Fyn High in "Gassum time".

Considering the above outlined geological model of the Gassum Formation in the Stenlille area as an analogue for the Havnsø structure, proximal-distal considerations in the depositional setting has to be taken into account. The Stenlille model can thus not act as a "one to one" model for the Havnsø structure as the more distal position of this structure compared to the Stenlille structure implies that not all of the reservoir sandstones present in Stenlille necessary extend to the Havnsø structure.

Sand sourced from the NE (within SQ´s 1 and 2) and from the SW (within SQ3) may have reached the area of the Havnsø structure too as this area and the Stenlille area were situated with roughly similar distances to the northern and southern basin margins. Sandstone intervals interpreted as reflecting progradation in westerly to north-westerly directions (mainly FSST and LST sandstones of SQ´s 4, 5 and 6) may very well extend to the Havnsø structure. Sandy FSST deposits of SQ4 and LST deposits of SQ5 might even be thicker developed in the Havnsø structure than in the Stenlille structure as SB5 probably represents a long period of marked erosion and basinwards bypass of sand. Gregersen et al. (2020) correlate the Base and Top Gassum reflector as well as the TS5 reflector on 2D seismic data from the Stenlille structure to the Havnsø structure. Their interpretations indicate that the Gassum Formation becomes considerably thicker when mapping the formation on 2D seismic sections from the Stenlille structure to the Havnsø structure (probably one and a half times as thick). However, it is mainly the upper part of the Gassum Formation, above TS5, which thickens towards Havnsø whereas the part below TS5 has a fairly similar thickness in the two structures. This suggests that sandstone deposits indeed may be concentrated below TS5 in the Havnsø structure. Above TS5, sandstone intervals are probably less in thickness and marine offshore mudstones most likely constitutes a significant greater proportion compared to the Gassum Formation in the Stenlille structure as pointed out by Gregersen et al. (2020). This is due to the more basinwards position of the Havnsø structure, the larger accommodation space available for deposition in this area and the fact that the succession above TS5 was formed during a period of overall backstepping. Thus, it is also very doubtful that sand of Sequence 7, here interpreted as deposited by shoreface progradation towards NW, did reach the Havnsø structure.

In conclusion, the thickest and highest concentration of reservoir sandstone intervals in the Havnsø structure most likely occur below TS5. These sandstones are probably very similar to those in the Stenlille structure as the sand was sourced from the same areas and some of the sand may represent redeposited sand from the Stenlille area. In addition, it is likely that some of the LST sandstone intervals extend over both structures. This emphasize the relevance of using the sandstones of the Gassum Formation in the Stenlille structure as analogues for sandstones in the Havnsø structure, e.g. for studying reservoir properties such as poro-perm and diagenesis analysis.

Suggestions for further work on the 3D seismic data

The confidence of the present mapping and interpretations of the Stenlille 3D survey may be improved considerably and add new and more detailed interpretations to the overall depositional setting as well as to the estimates of the likelihood of sand being brought out to the Havnsø structure area by:

- constructing time-depth(m) relationships which place all of the Stenlille wells correctly relatively to the 3D seismic data and with a correct thickness of the stratigraphic intervals, e.g. of the Gassum Formation, relatively to the seismic data. This will be a major help in controlling and adjusting the present detailed mapping of sequences which more or less is based entirely on the Stenlille-19 well (at present the only well which correlate correctly with the seismic data).
- focussing more on the identification and interpretation of seismic facies/features (small-scale mounds, channels etc.) within individual sequences, than done in the present mapping of the 3D survey, may add further information to the interpretation of depositional environments.
- including many more seismic lines in the mapping of sequence stratigraphic surfaces thereby ensuring a much smaller spacing between interpreted seismic lines (in general, only every fifth or tenth line is interpreted at present). This may reveal features that at present are not observable when time-structural and time-thickness ms TWT maps are constructed, e.g. the appearance of “smaller” channels and the orientations of these – an important input for interpreting depositional environments and estimating the likelihood of sediments being bypassed to the Havnsø structure.
- constructing series of amplitude maps with certain ms TWT intervals below and above the present time-depth maps may further reveal features such as channels and orientations of e.g. progradational clinoforms.
- processing and interpretating additional data on palynofacies and well cores and integrating these with the 3D seismic data.

As suggested by Gregersen et al. (2020), a new 2D seismic line direct from the Stenlille-19 well to a new 3D seismic survey covering the Havnsø structure would form an outstanding dataset for improving our understanding of the regional depositional setting and ensure that the many Stenlille data can be transferred to the Havnsø structure in the most qualified way.

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Figures

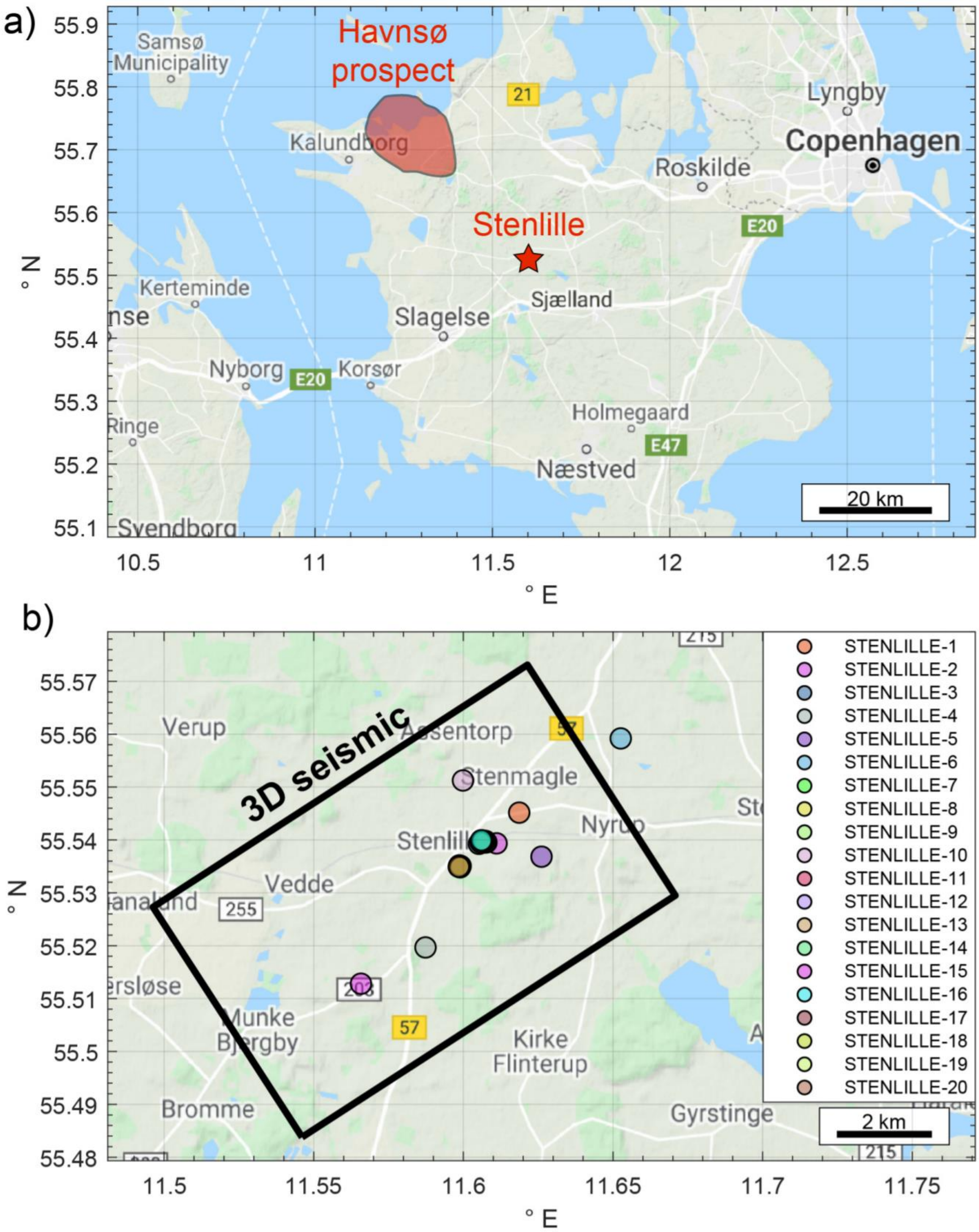

Fig.1. Location maps of (a) Sjælland with the Havnsø prospect outlined and the Stenlille area marked, and (b) zoom-in at the Stenlille area with well positions and the 3D seismic survey. Many wells have approximately the same position and plots on top of each other on the map. From Bredesen (submitted).

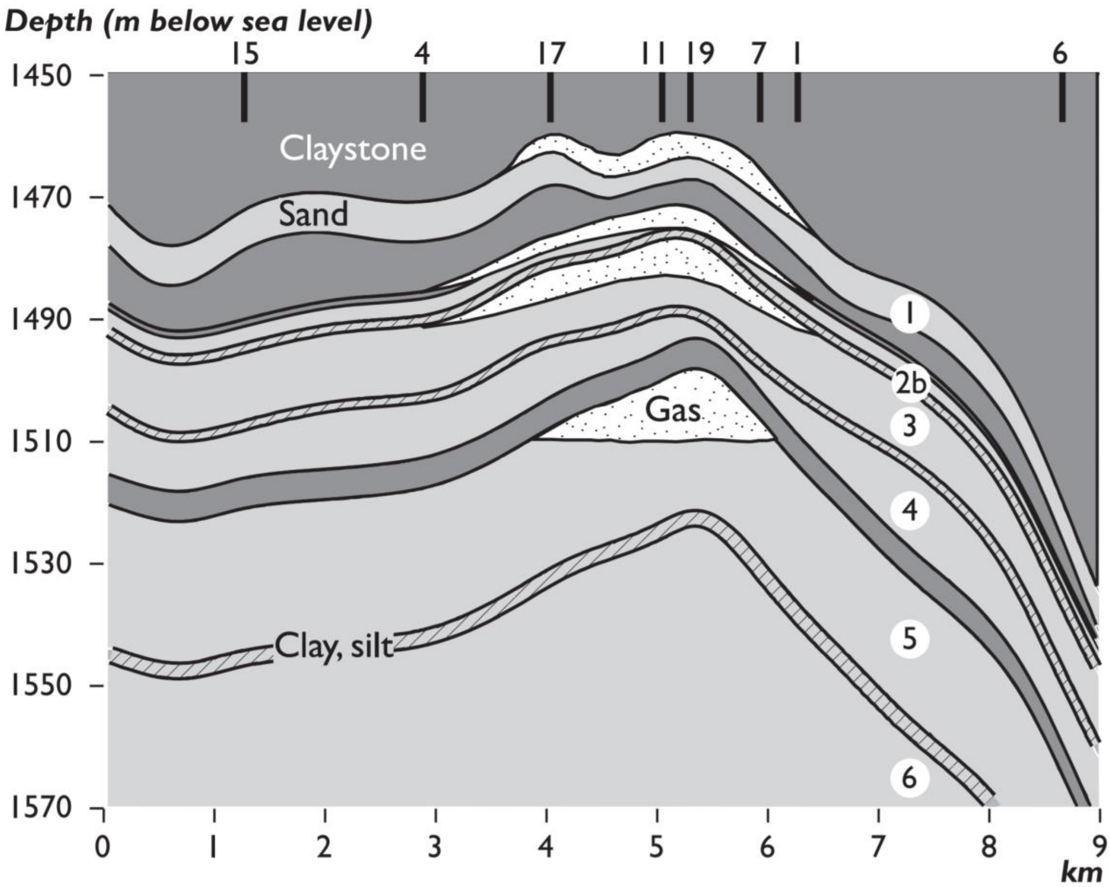

Fig. 2. Schematic cross section (SW–NE) of the Stenlille natural gas underground storage showing the various reservoir zones and with well locations indicated at the top of the figure. Depth is below mean sea level. From Bredesen (submitted) extracted from Laier & Øbro (2009).

Basemap

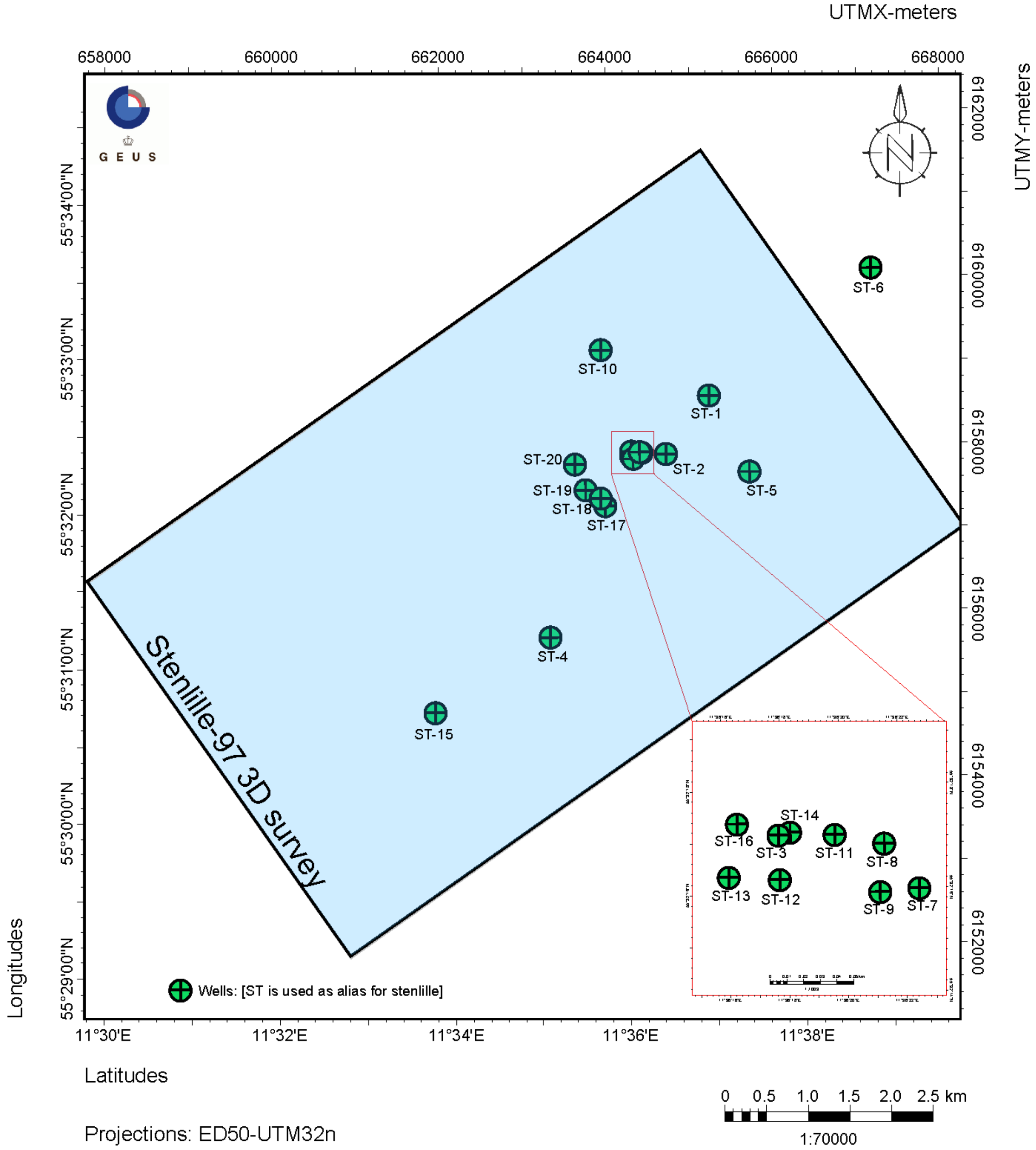

Fig. 3. Map showing the extend of the 3D seismic database and position of Stenlille wells.

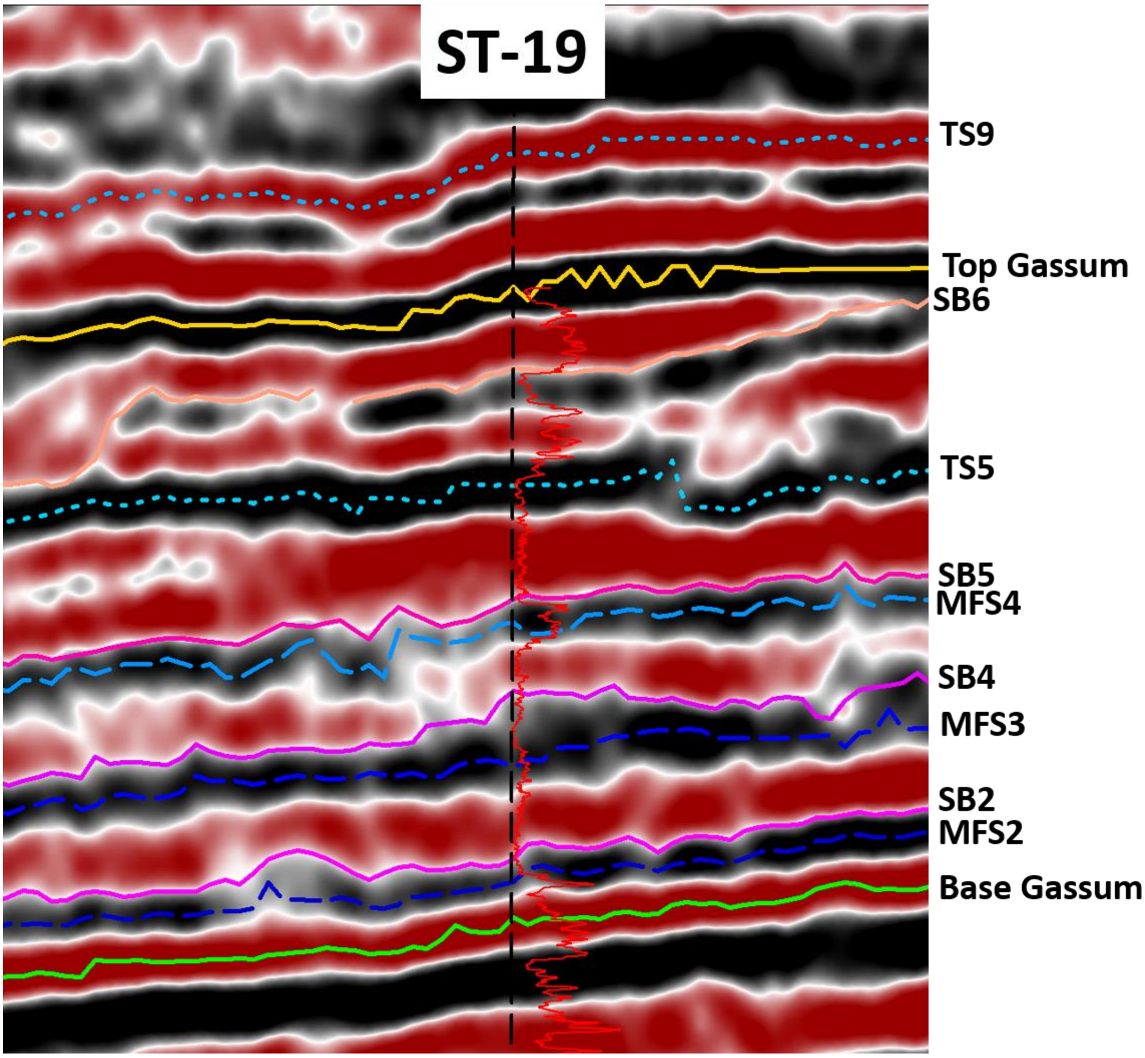

Fig. 4. Zoom in on the gamma-ray log of the Stenlille-19 well (ST-19) with the seismic InLine section 1157 as background and interpreted seismic horizons (the whole seismic section with horizontal and vertical scales is shown in Figure 19). ST-19 is the only Stenlille well which is considered to correlate correctly with the 3D seismic survey.

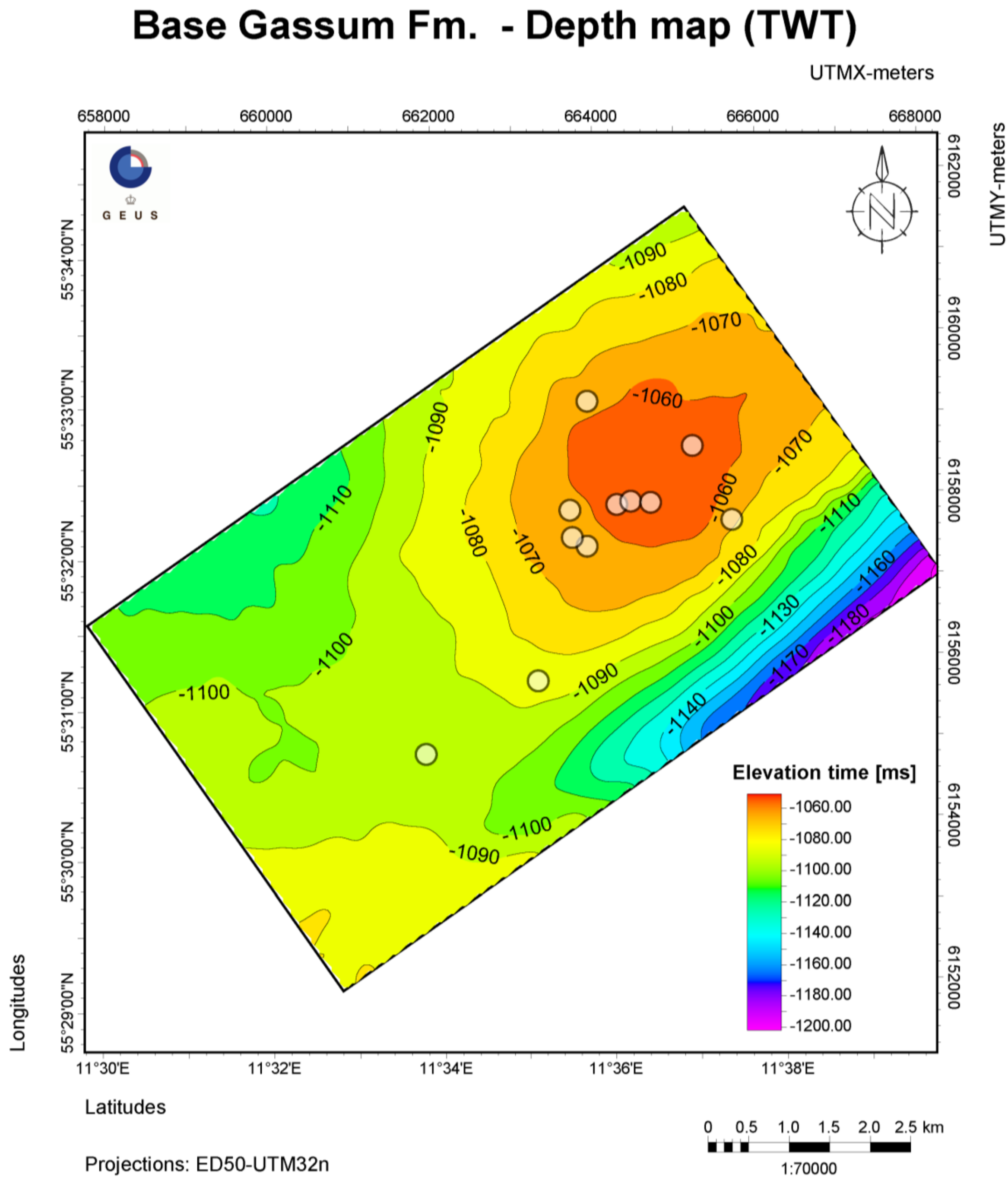

Fig. 5. Base Gassum Fm – Time-structural map in two-way travel time (milliseconds).

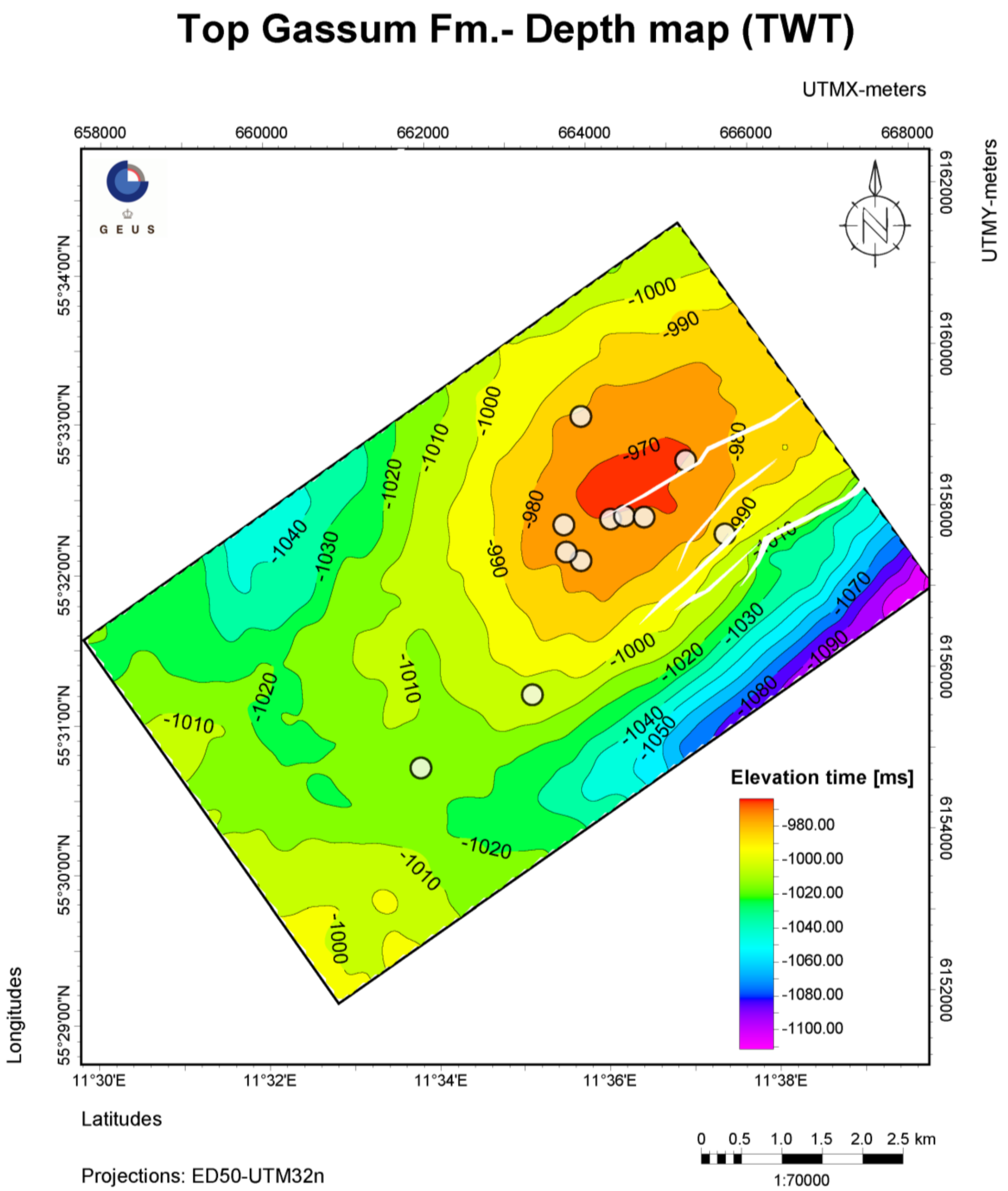

Fig. 6. Top Gassum Fm – time-structural map in two-way travel time (milliseconds). Faults, seen as white lines, are from Gregersen et al. (2020).

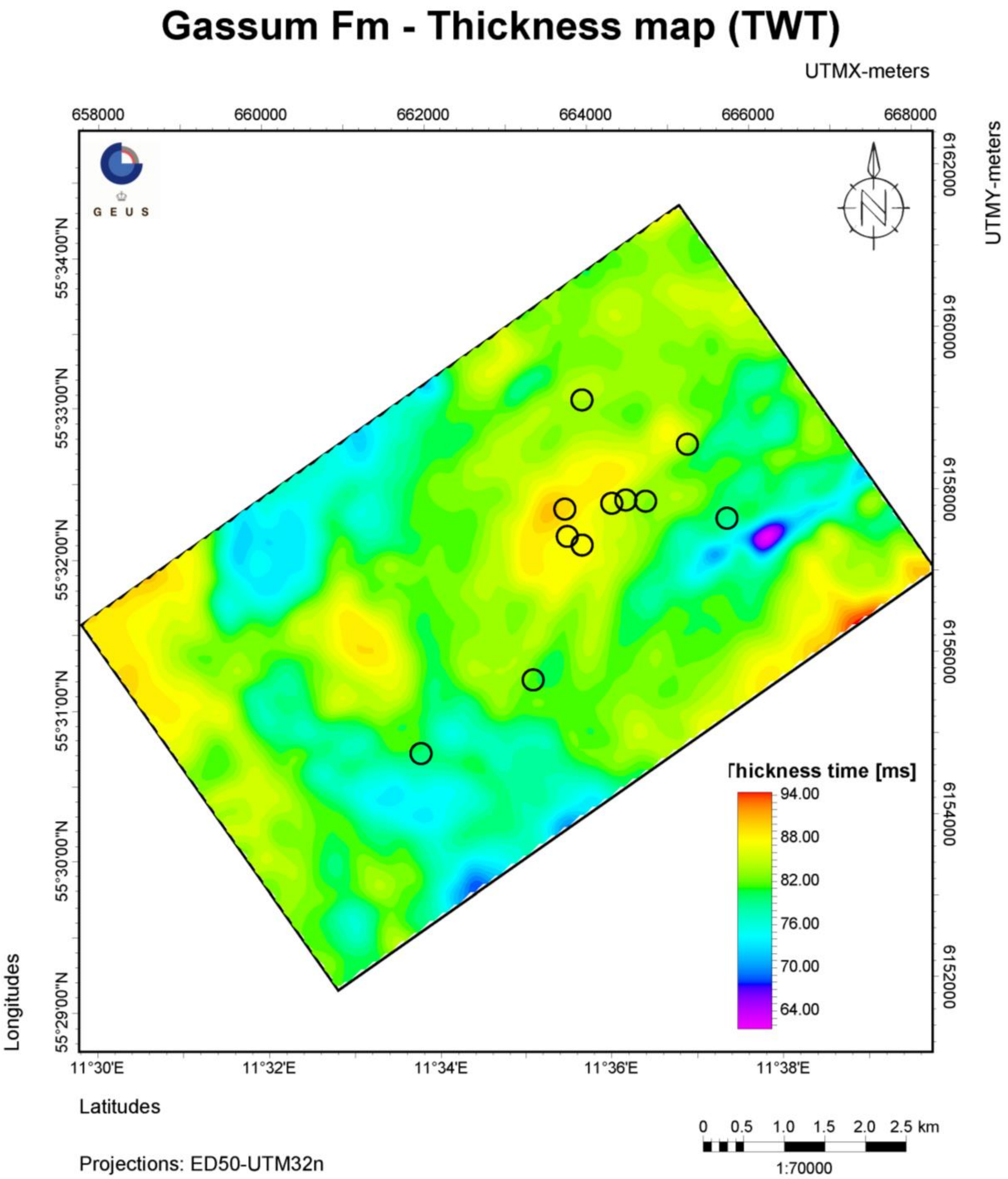

Fig. 7. Gassum Fm – time-thickness map in two-way travel time (milliseconds) between the Top Gassum and Base Gassum surfaces.

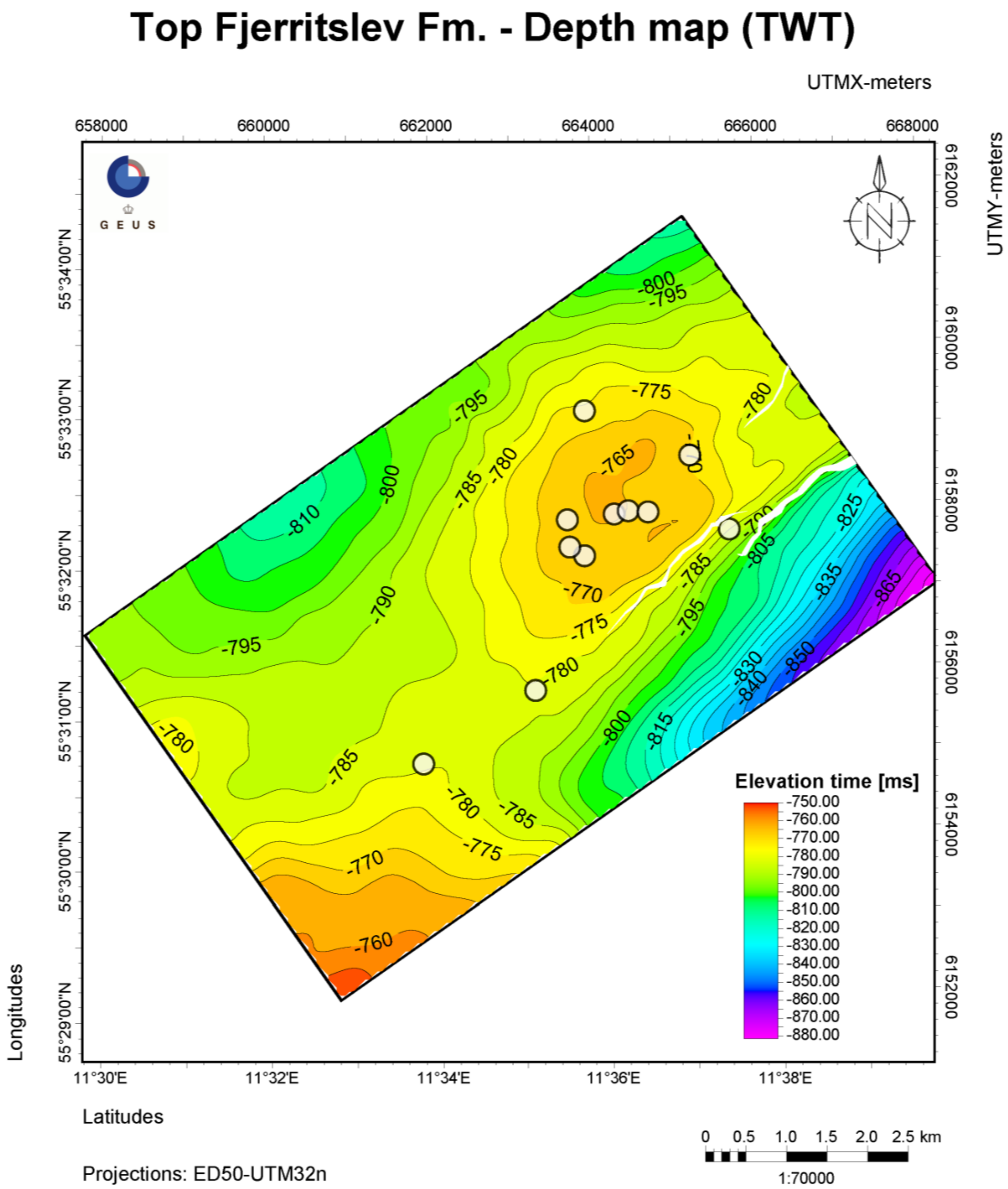

Fig. 8. Top Fjerritslev Fm – time-structural map in two-way travel time (milliseconds). Faults, seen as white lines, are from Gregersen et al. (2020).

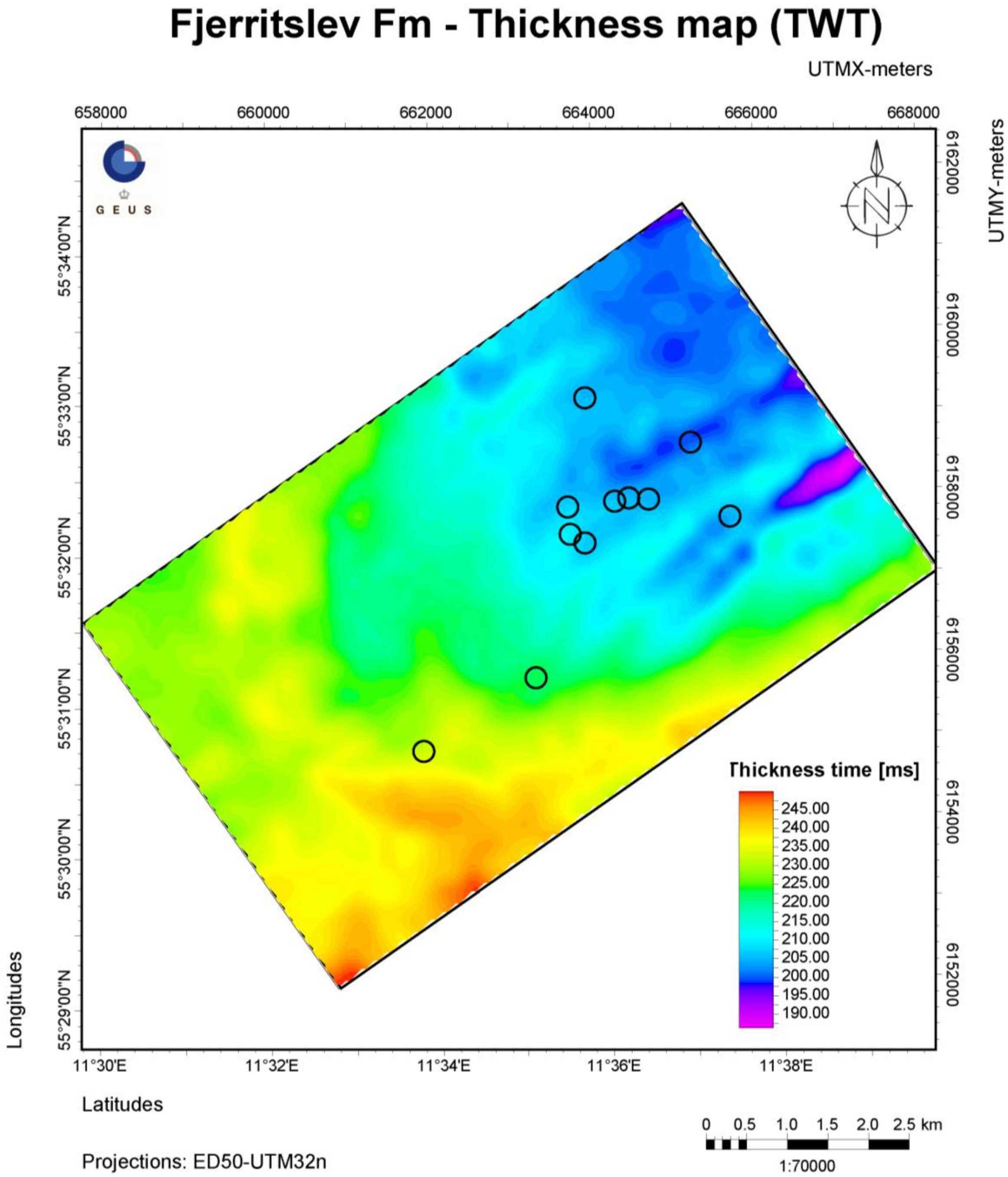

Fig. 9. Fjerritslev Fm – time-thickness map in two-way travel time (milliseconds) between the Top Fjerritslev and Top Gassum surfaces.

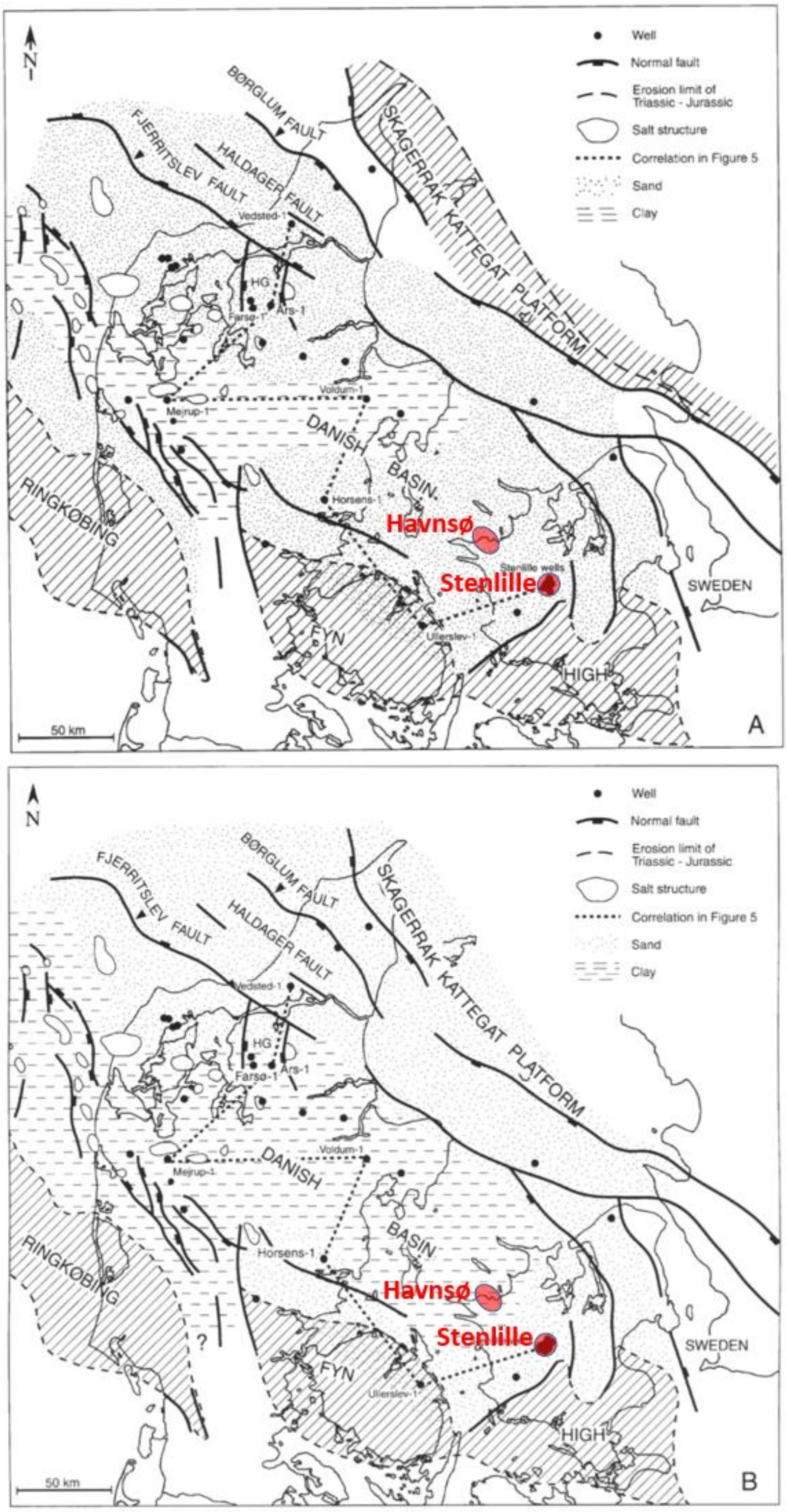

Fig. 10. Palaeogeographic reconstructions of Uppermost Triassic lowstand situations and maximum extent of A) sandstones of Sequence 6, and B) sandstones of Sequence 7. The Havnsø structure is located c. 30 km NW of the Stenlille structure and represents a more basinwards position compared to Stenlille at the time the sediments of the Gassum Formation were deposited. Both structures are located in the eastern part of the Danish Basin, between the Ringkøbing–Fyn High and the Sorgenfrei–Tornquist Zone. From Hamberg & Nielsen (2000) with roughly positions of Stenlille and Havnsø structures added.

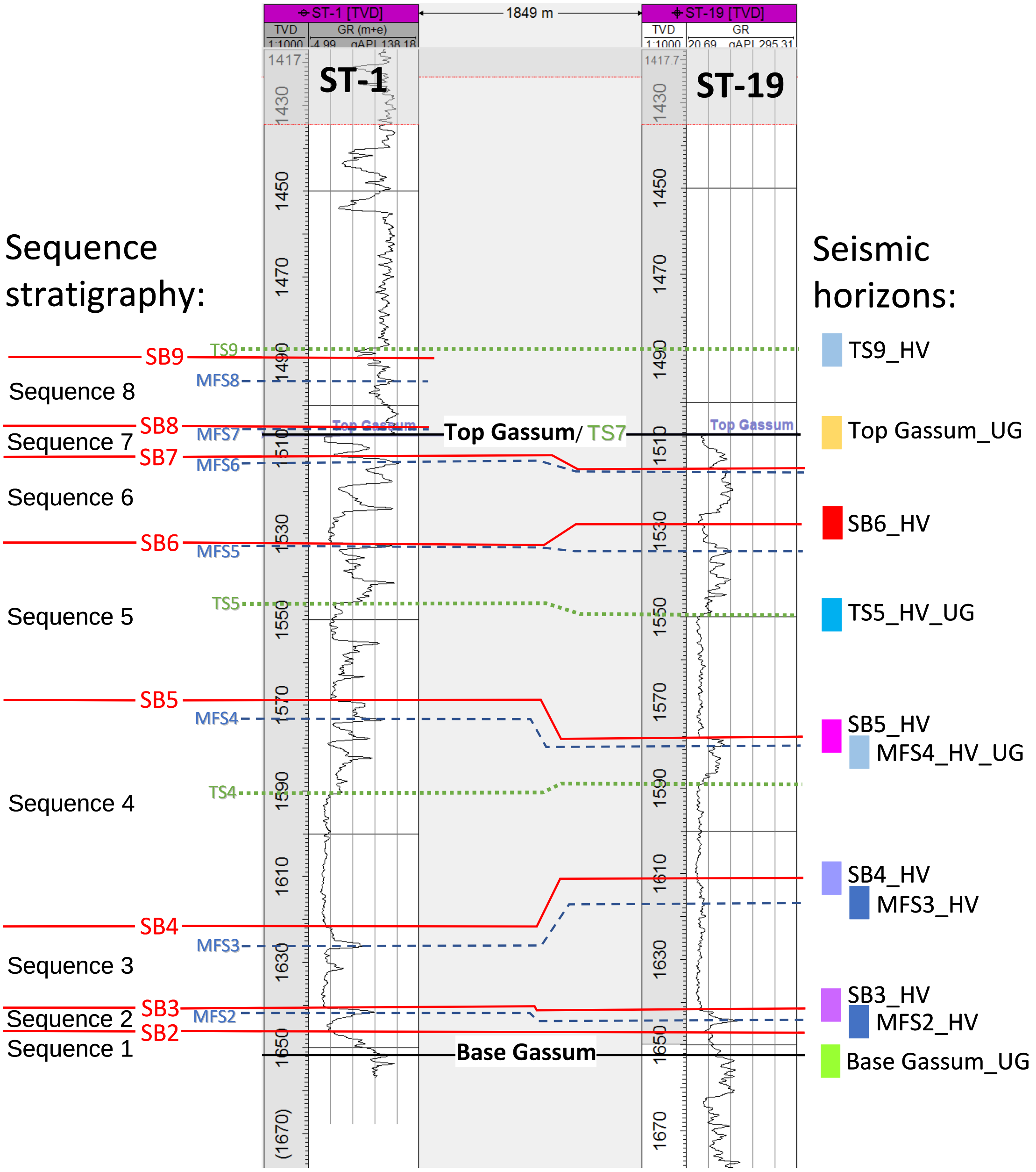

Fig. 11. Stenlille-1 (ST-1) and (ST-19) wells with gamma-ray log (GR), and well-tied sequence stratigraphic surfaces and to the right interpreted seismic horizons with the first part of the horizon names marking, which sequence stratigraphic surface they represent.

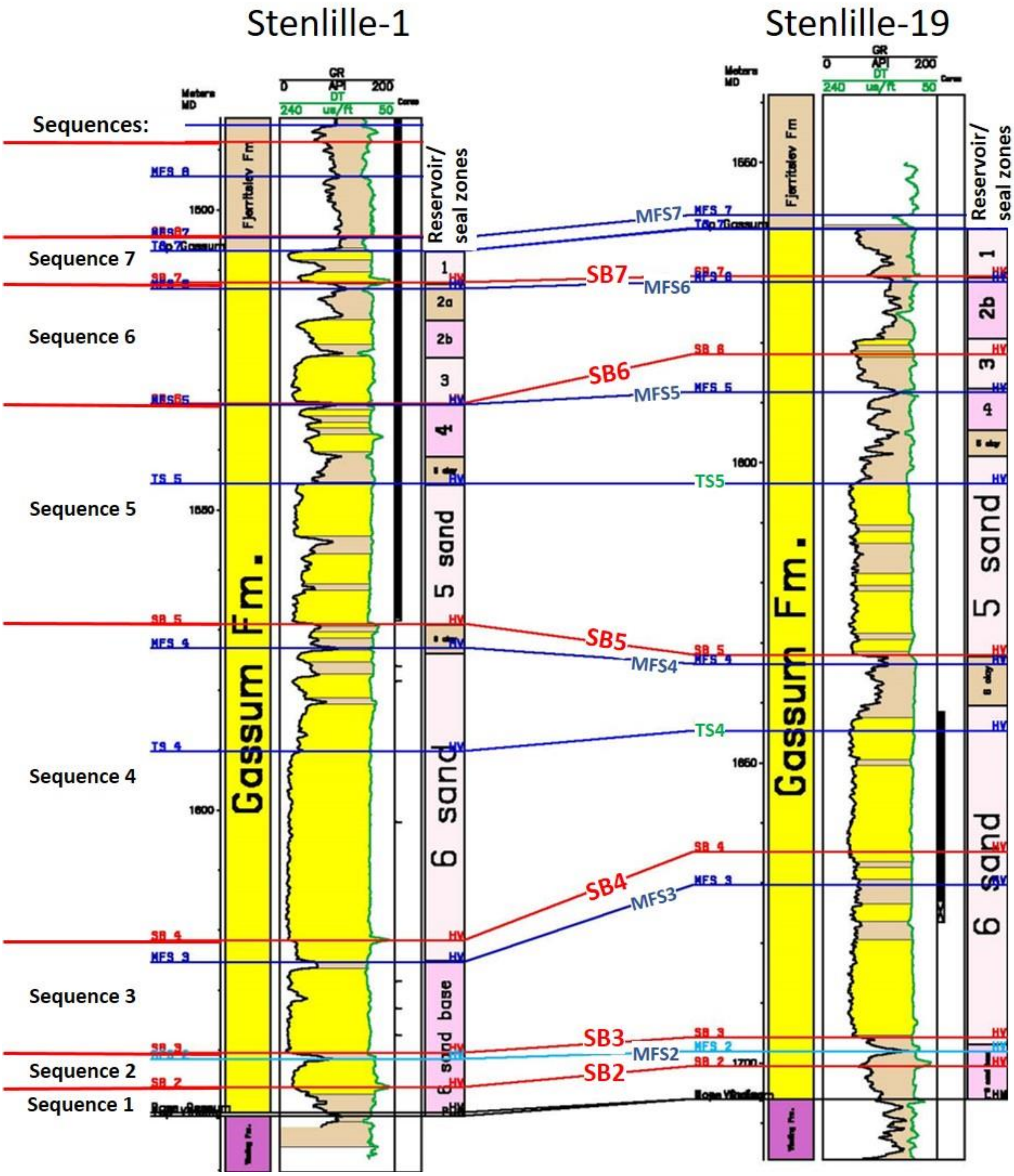

Fig. 12. Stenlille-1 and Stenlille-19 wells with gamma-ray log (GR) and sonic log (DT), well-tied sequence stratigraphic surfaces and sequences and DONG´s reservoir/seal zones (1–6). Yellow and brown, filling out the space between GR and DT logs, indicate intervals dominated by sandstone and mudstone, respectively. SB: sequence boundary, MFS: Maximum flooding surface, TS: Transgressive surface.

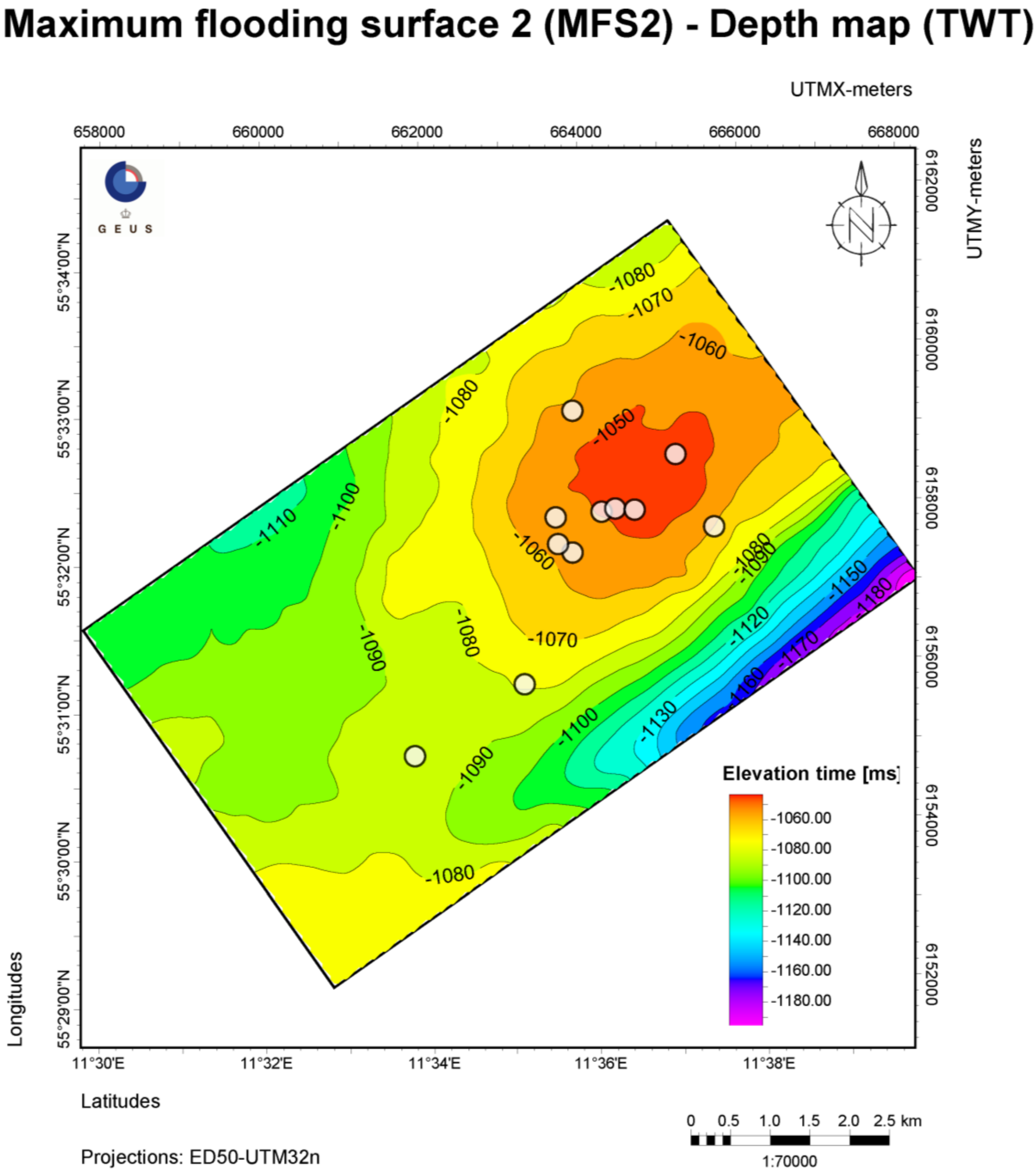

Fig. 13. Maximum flooding surface 2 – MFS2 – time-structural map in two-way travel time (milliseconds).

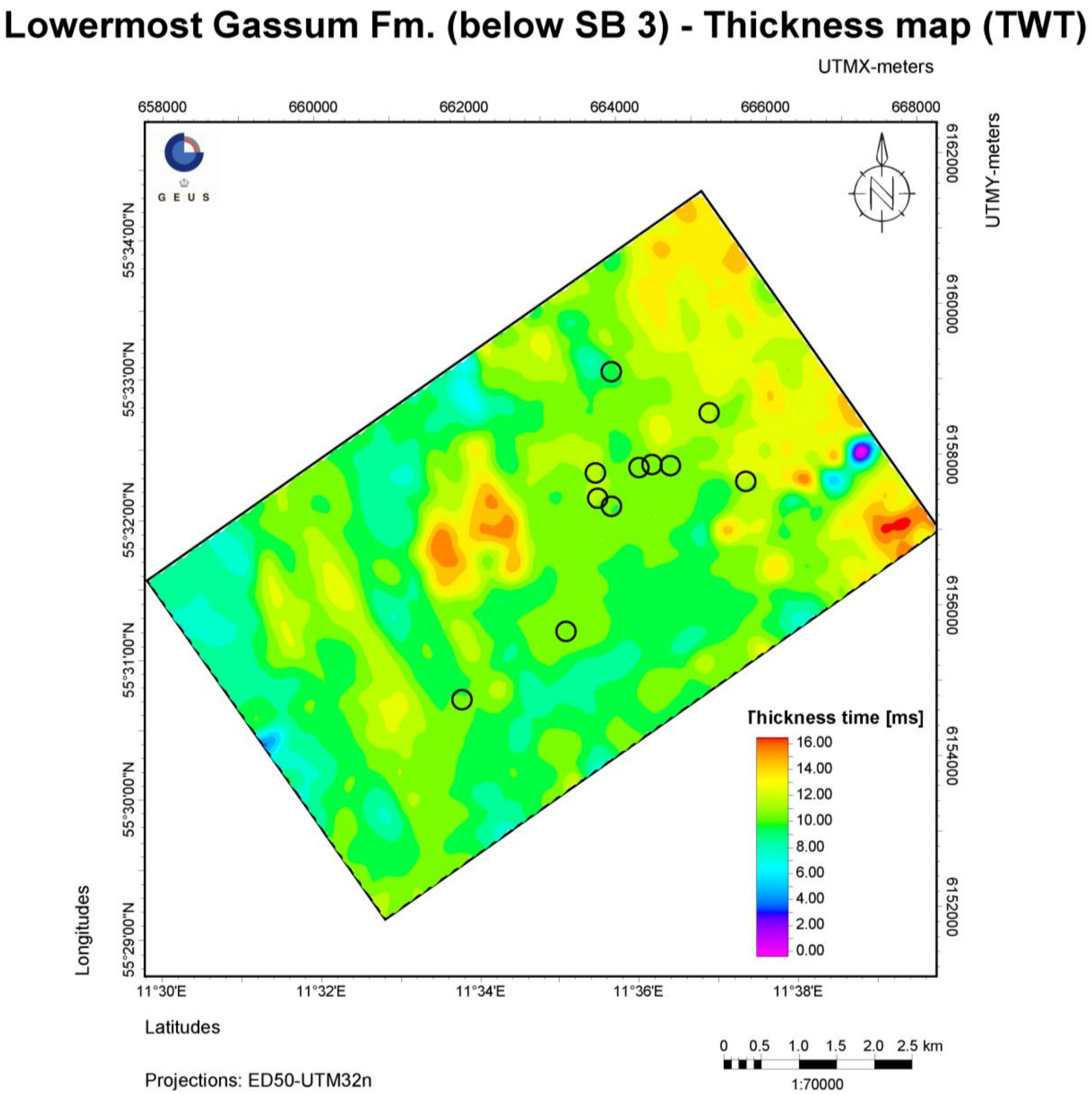

Fig. 14. Map showing the time-thicknesses between the SB3 and Base Gassum surfaces in two-way travel time (milliseconds).

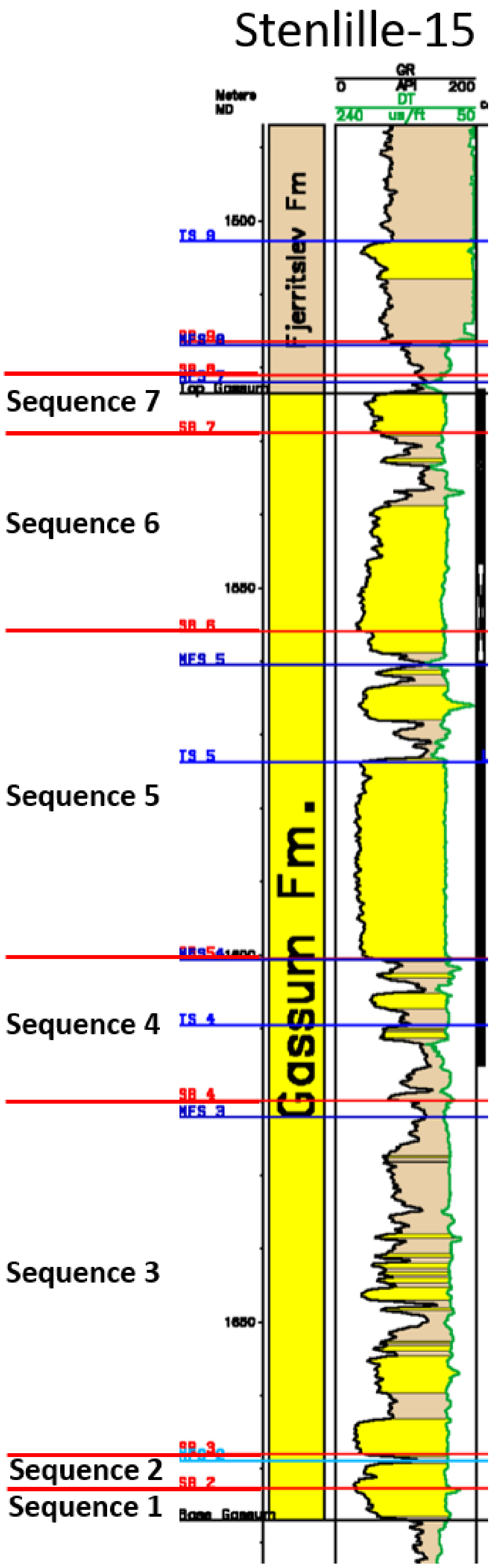

Fig. 15. The Stenlille-15 well (ST-15) with gamma-ray log (GR) and sonic log (DT) and interpreted sequence stratigraphic surfaces. Sequence 3 is atypical in this well compared to the other Stenlille wells as it is especially thick, up to around 50 m, and consists of mudstone and subordinate sandstone intervals (e,g, compare with Sequence 3 in the Stenlille-1 and Stenlille-19 wells in Fig. 12).

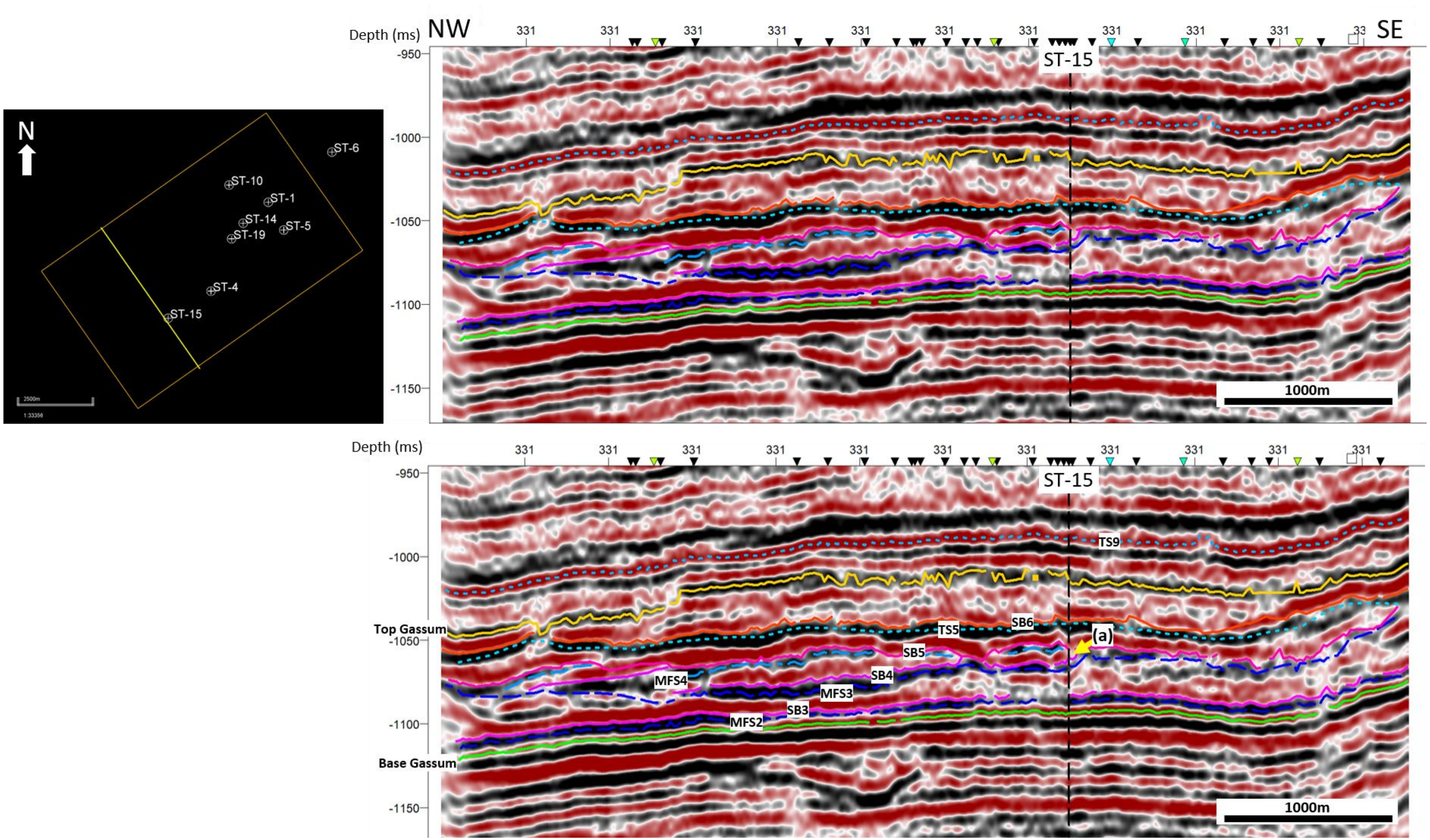

Fig. 16. NW–SE trending seismic section (XLine 331) passing through the Stenlille-15 well marked with a black stippled line. Note among others (a) SQ4, containing a large part of the sandstone package in reservoir zone 6, is very thin in the Stenlille-15 well (in contrast to all the other Stenlille wells where a thick edition of SQ4 is present). In contrast, the underlying SQ3 is considerably thicker in Stenlille-15 than in the remaining Stenlille wells. Depth is in two-way travel time (milliseconds). Shown with a vertical exaggeration of 10.

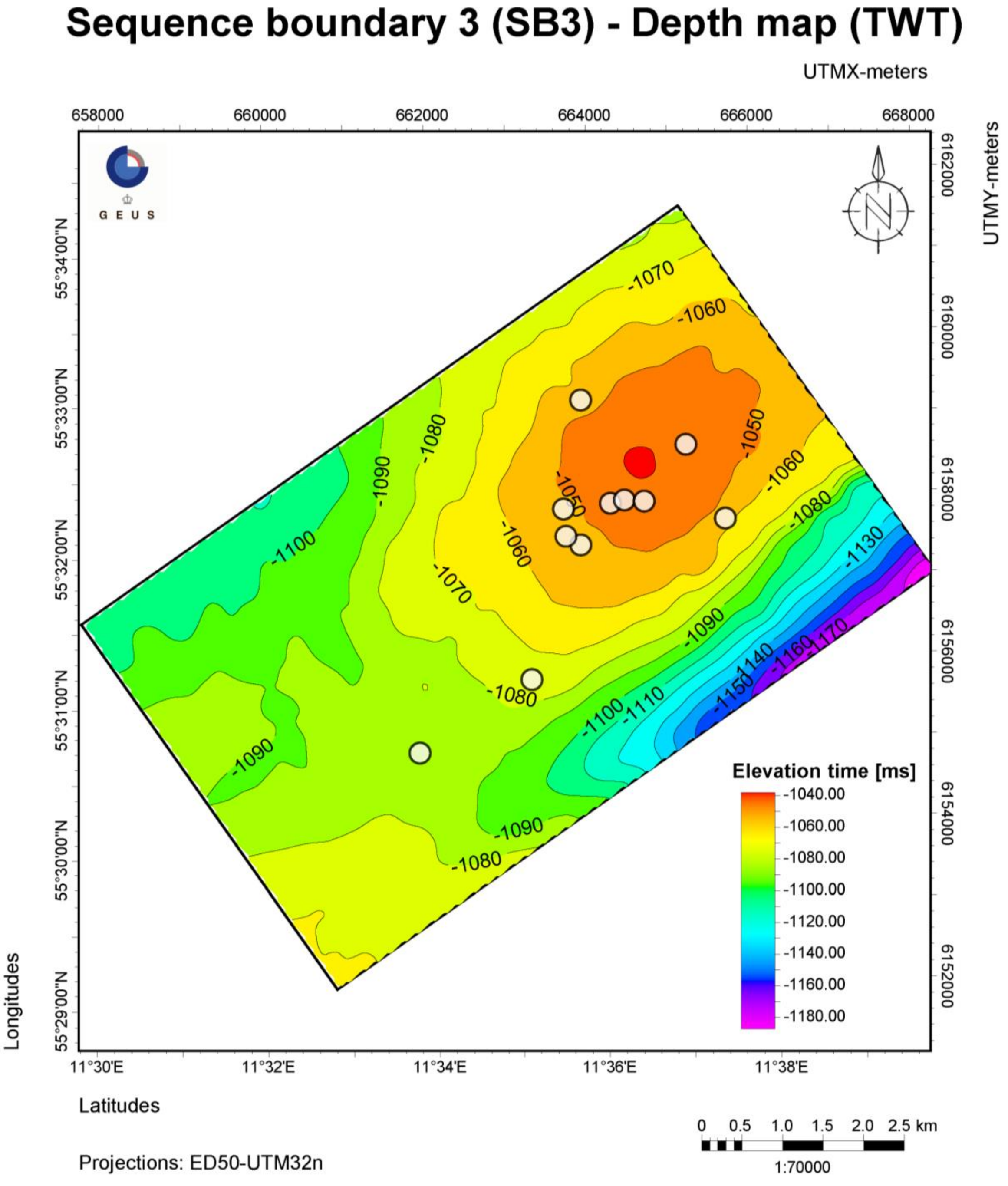

Fig. 17. Sequence boundary 3 - SB3 – time-structural map in two-way travel time (milliseconds).

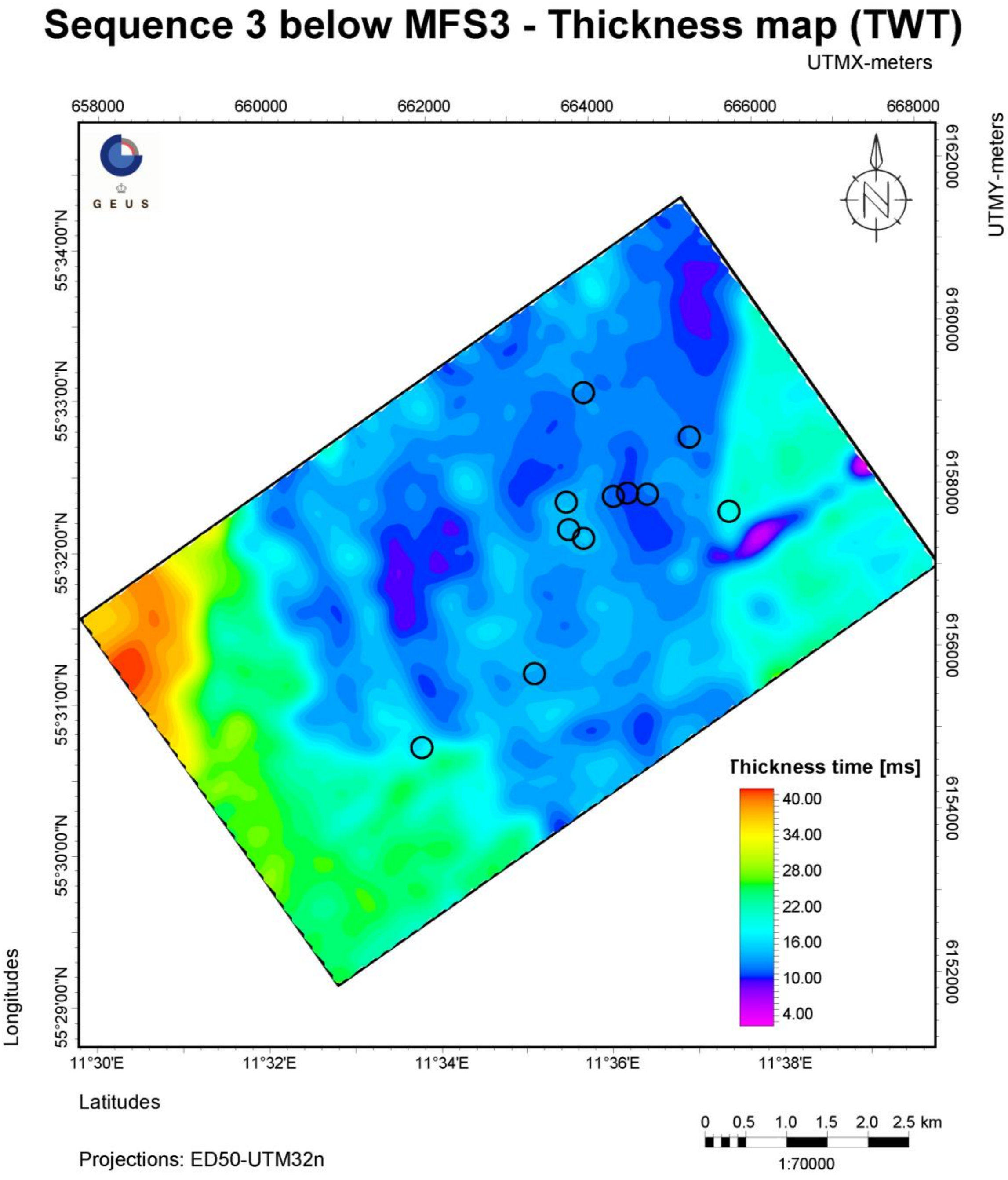

Fig. 18. Map showing the time thicknesses between the MFS3 and SB3 surfaces in two-way travel time (milliseconds).

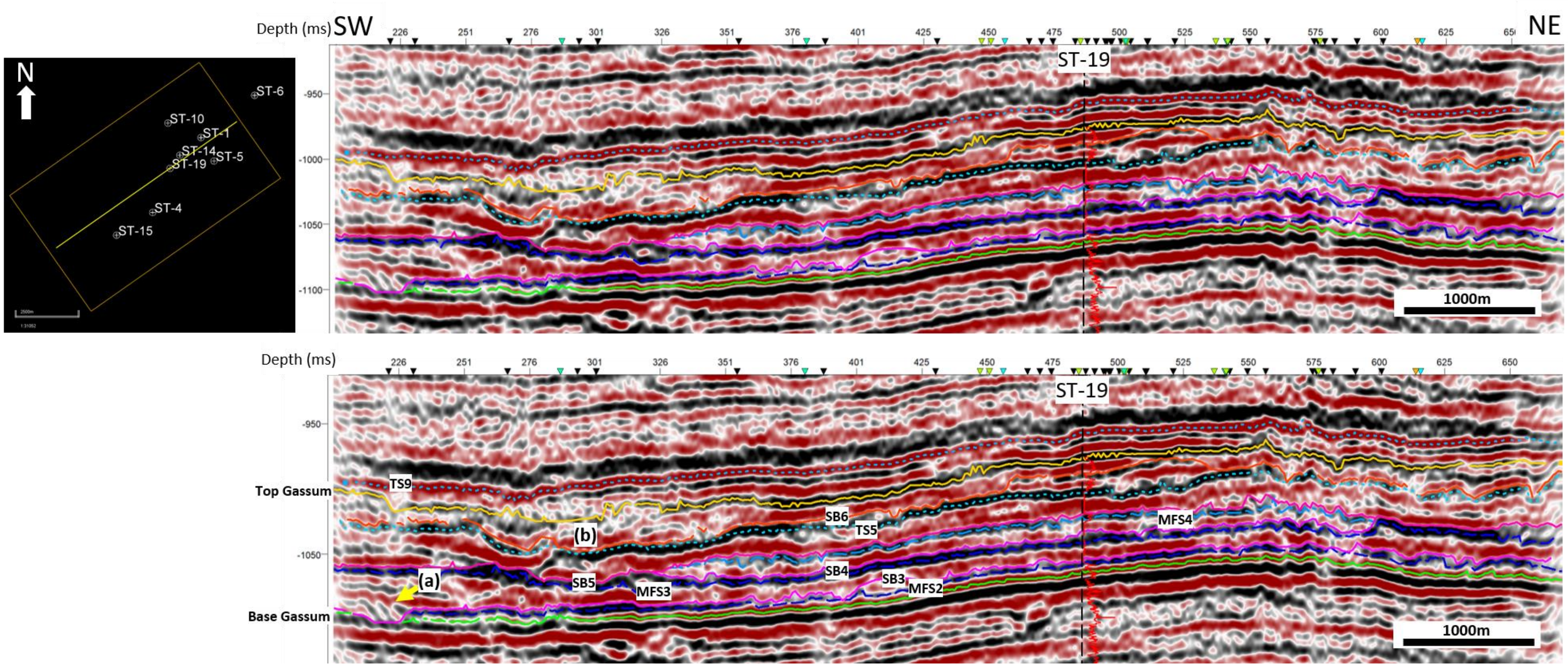

Fig. 19. SW–NE trending seismic section (InLine 1157) passing through the Stenlille-19 well. Note among others (a) SB3 truncating SQ2 and above SB3 reflectors are seen to dip towards the NE; (b) the broad shallow channel appearance of SB6 where Sequence 6 is very thick but which does not necessary reflect deep valley incision but merely the infilling of an existing relief as discussed in the text. Depth is in two-way travel time (milliseconds). Shown with a vertical exaggeration of 10.

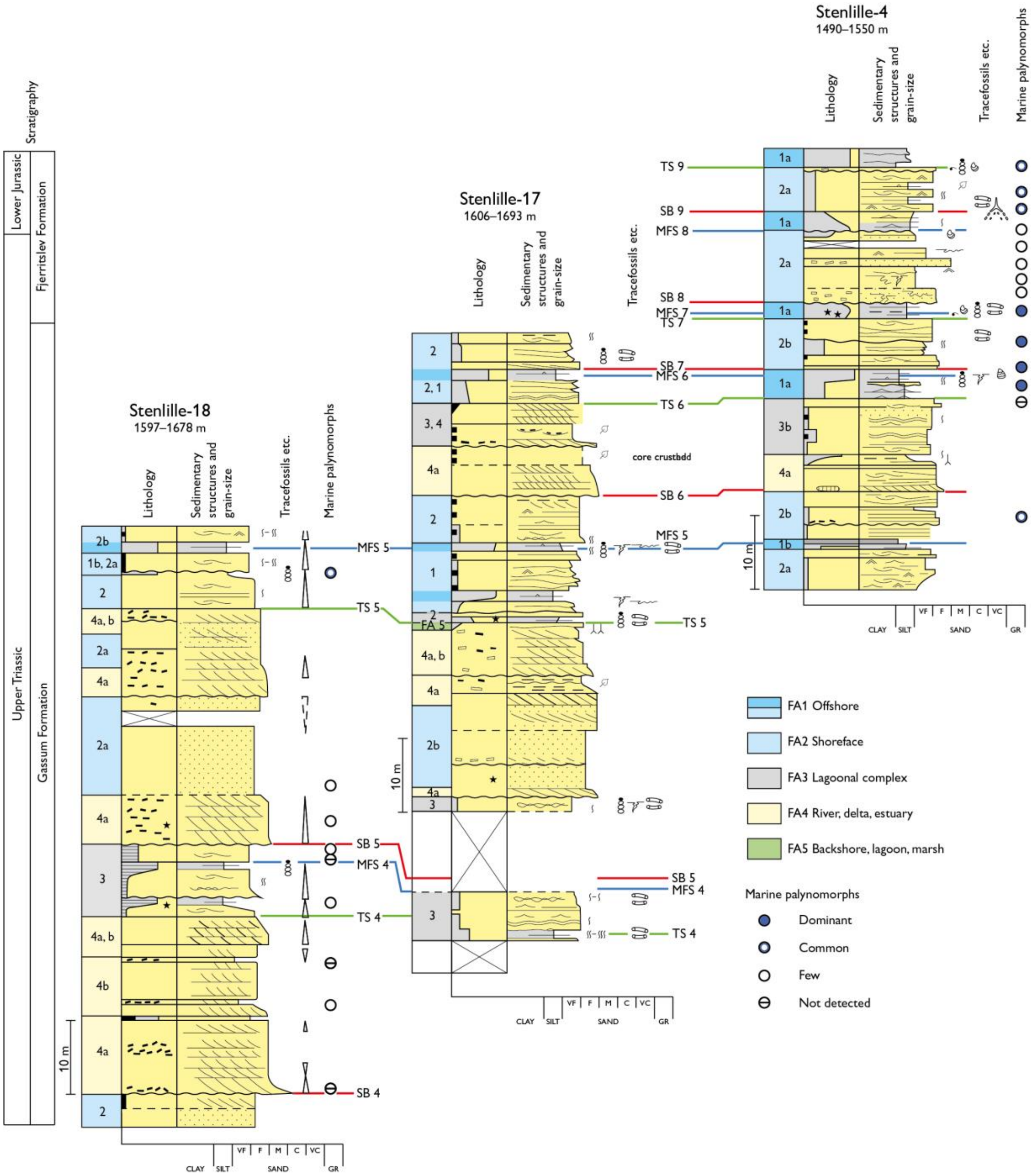

Fig. 20. Summary sedimentological core section through the main part of the Gassum Formation and basal part of the Fjerritslev Formation with lithology, sedimentary structures, overall depositional environments, sequence stratigraphic surfaces etc. marked. From Hovikoski & Pedersen (2020).

Sequence boundary 4 (SB4) - Depth map (TWT)

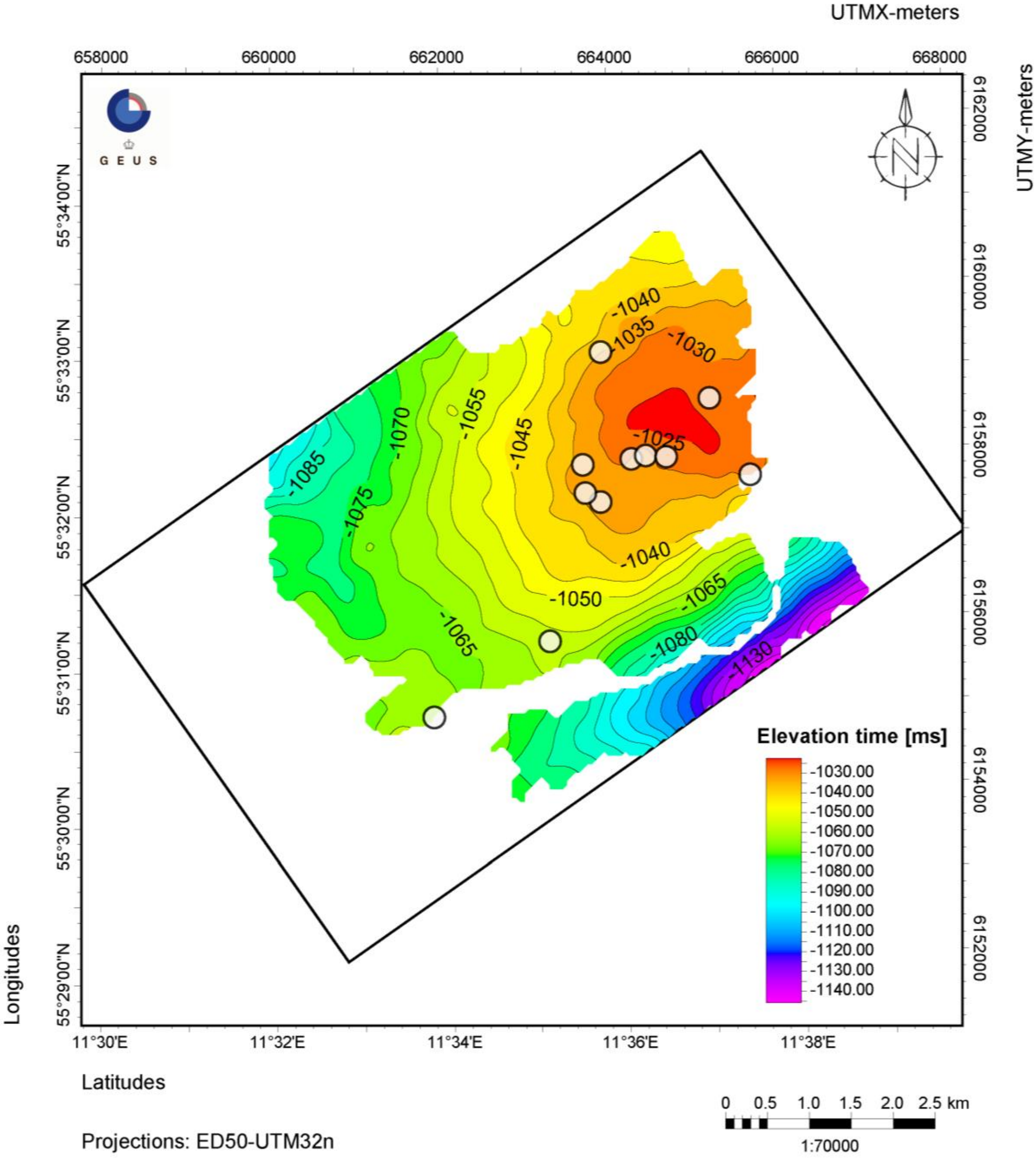

Fig. 21. Sequence boundary 4 – SB4 – time-structural map in two-way travel time (milliseconds).

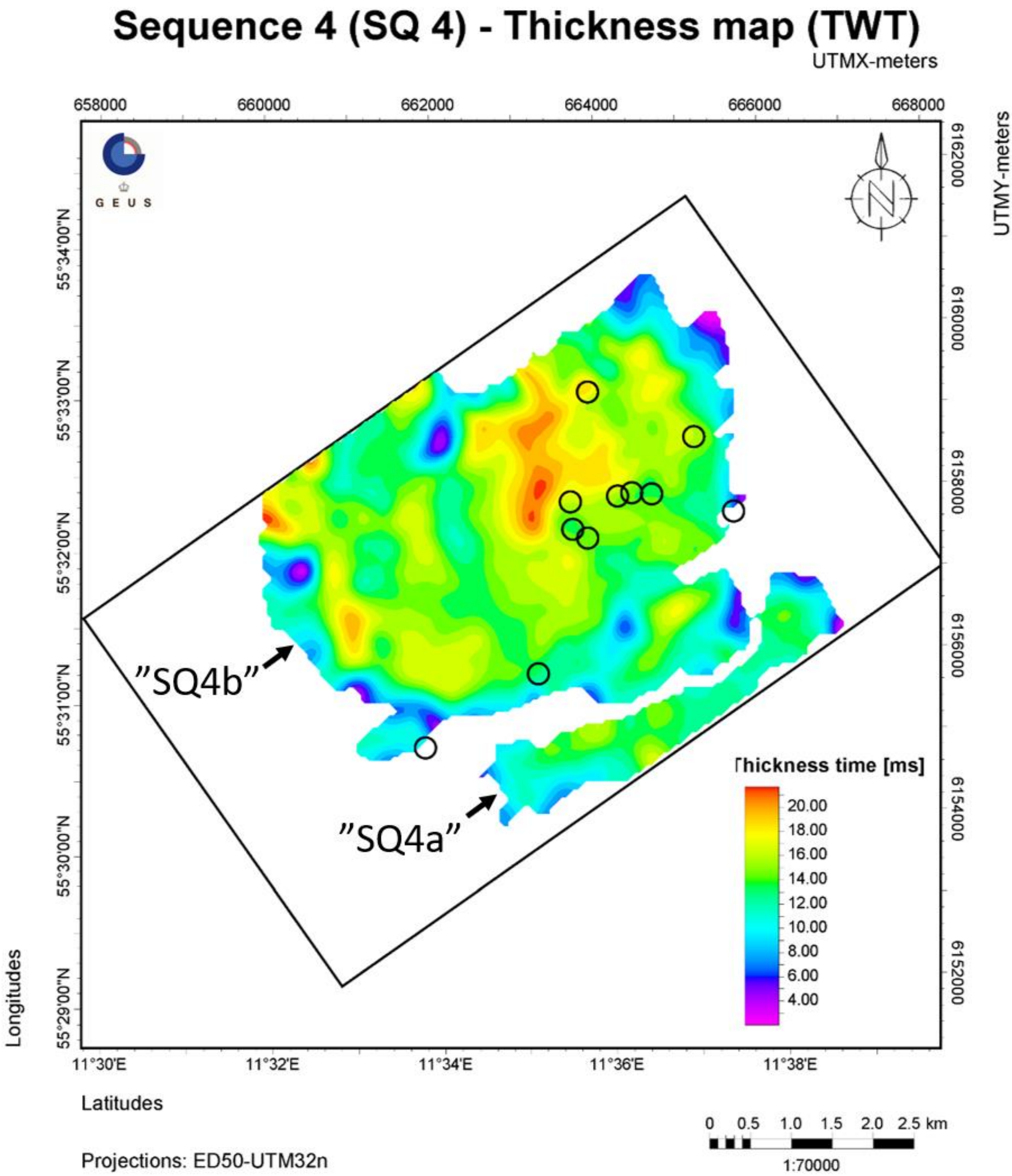

Fig. 22. Sequence 4 – SQ4 – time-thickness map in two-way travel time (milliseconds) between the SB5 and SB4 surfaces. The distribution of SQ4 is shown as two polygons, marked as "SQ4a" and "SQ4b", interpreted to represent the areal extent within the 3D survey of two progradational depositional events towards the NW as discussed in the text.

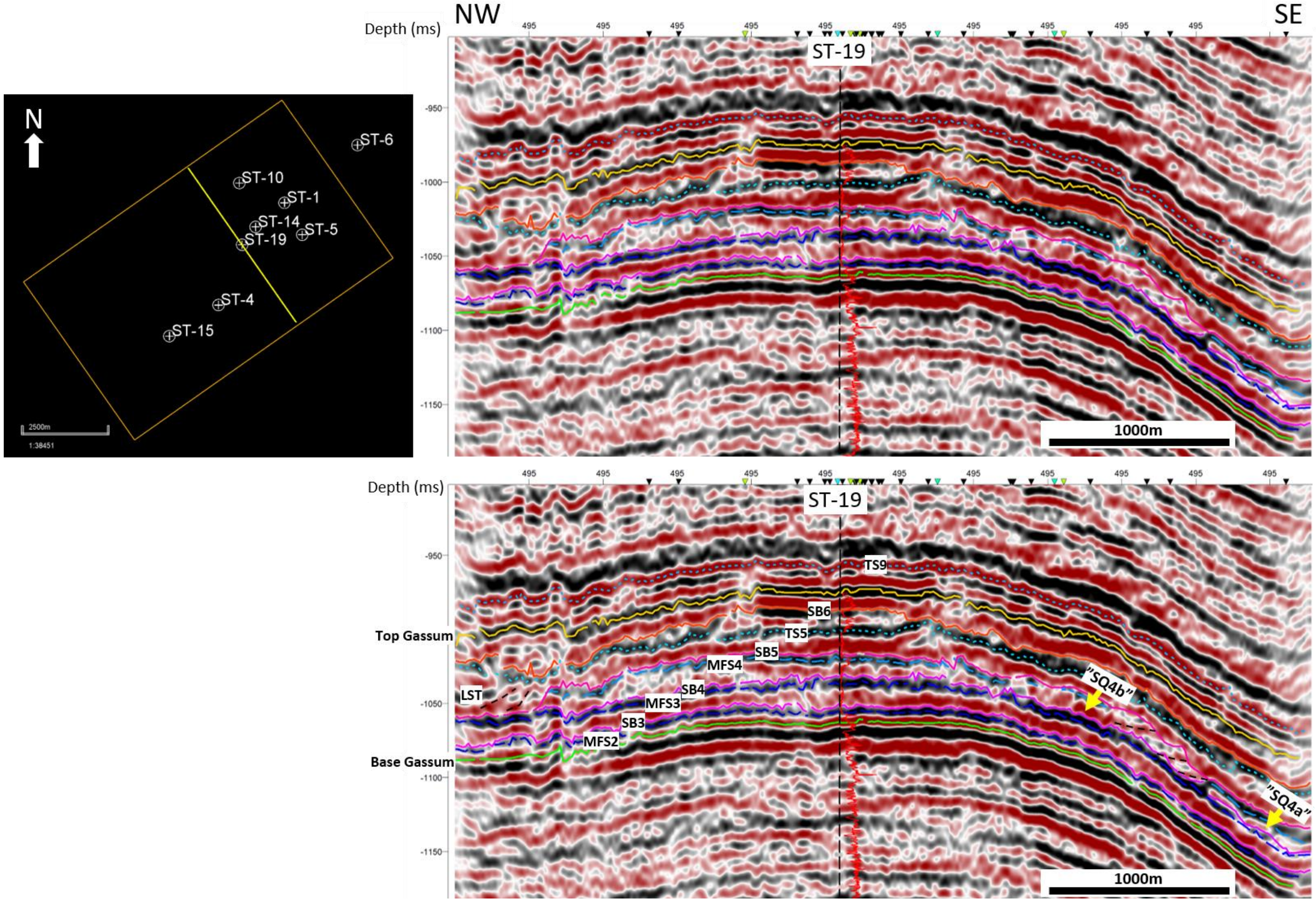

Fig. 23 NW–SE trending seismic section (XLine 495) passing through the Stenlille-19 well. Note among others a) the interpretation of two progradational events within SQ4, marked as "SQ4a" and "SQ4b" on the section; b) the local occurrence of subtle reflectors dipping towards the NW within SQ4 (marked with black stippled lines); c) the truncation of SQ4 by SB5 in the north-westernmost part of the section and above this the occurrence of subtle NW-wards dipping reflectors (marked with black stippled lines) of the LST of SQ5. Depth is in two-way travel time (milliseconds). Shown with a vertical exaggeration of 10.

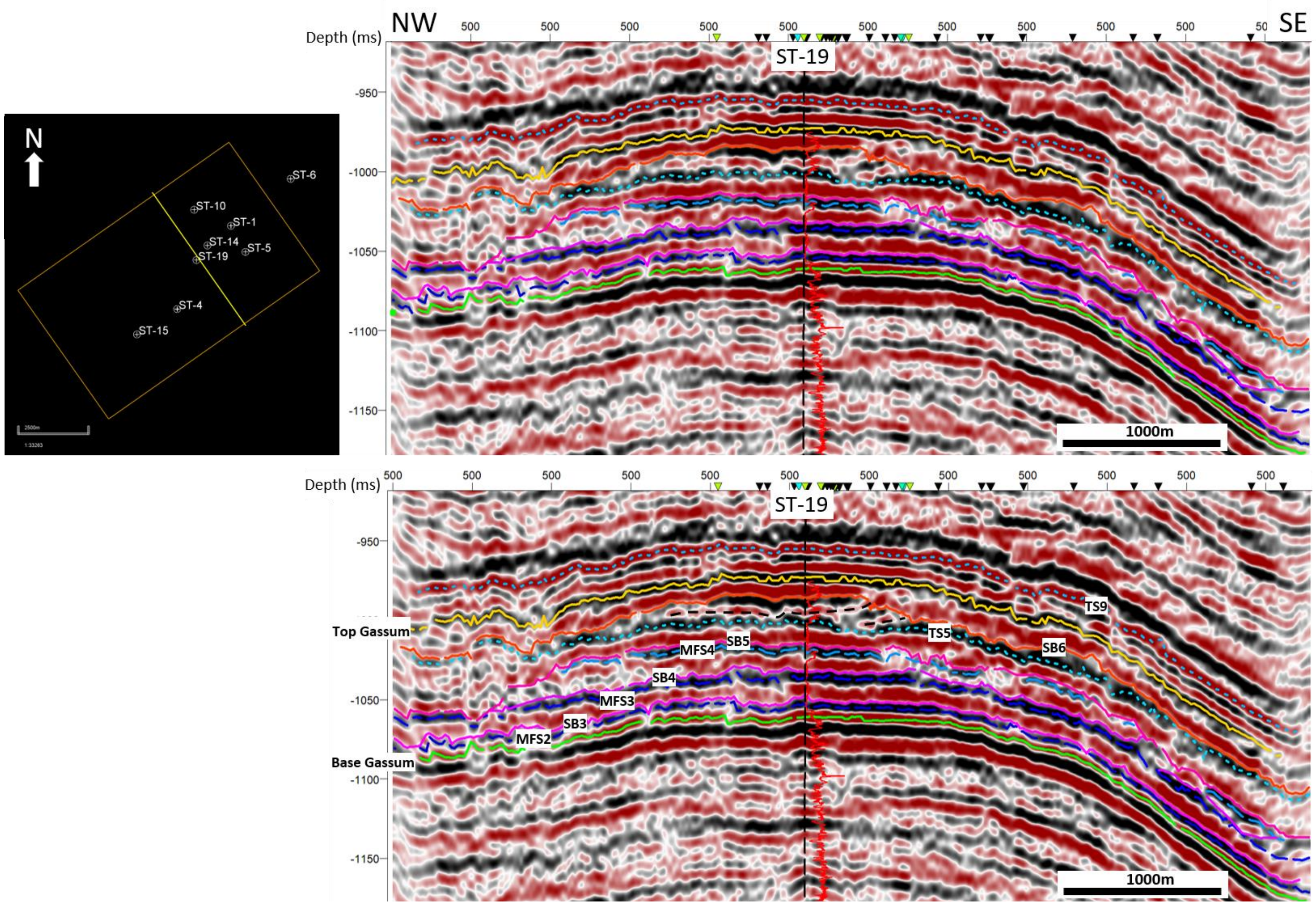

Fig. 24. NW–SE trending seismic section (XLine 500) passing through the Stenlille-19 well. Note the occurrence of reflectors extending downwards from SB6 (marked with black stippled lines) and pinching out towards the NW. These probably represent falling stage systems tract deposits of Sequence 5, recording stepwise shoreline progradation towards the NW under a general sea-level fall (in the end leading to the formation of SB6). Depth is in two-way travel time (milliseconds). Shown with a vertical exaggeration of 10.

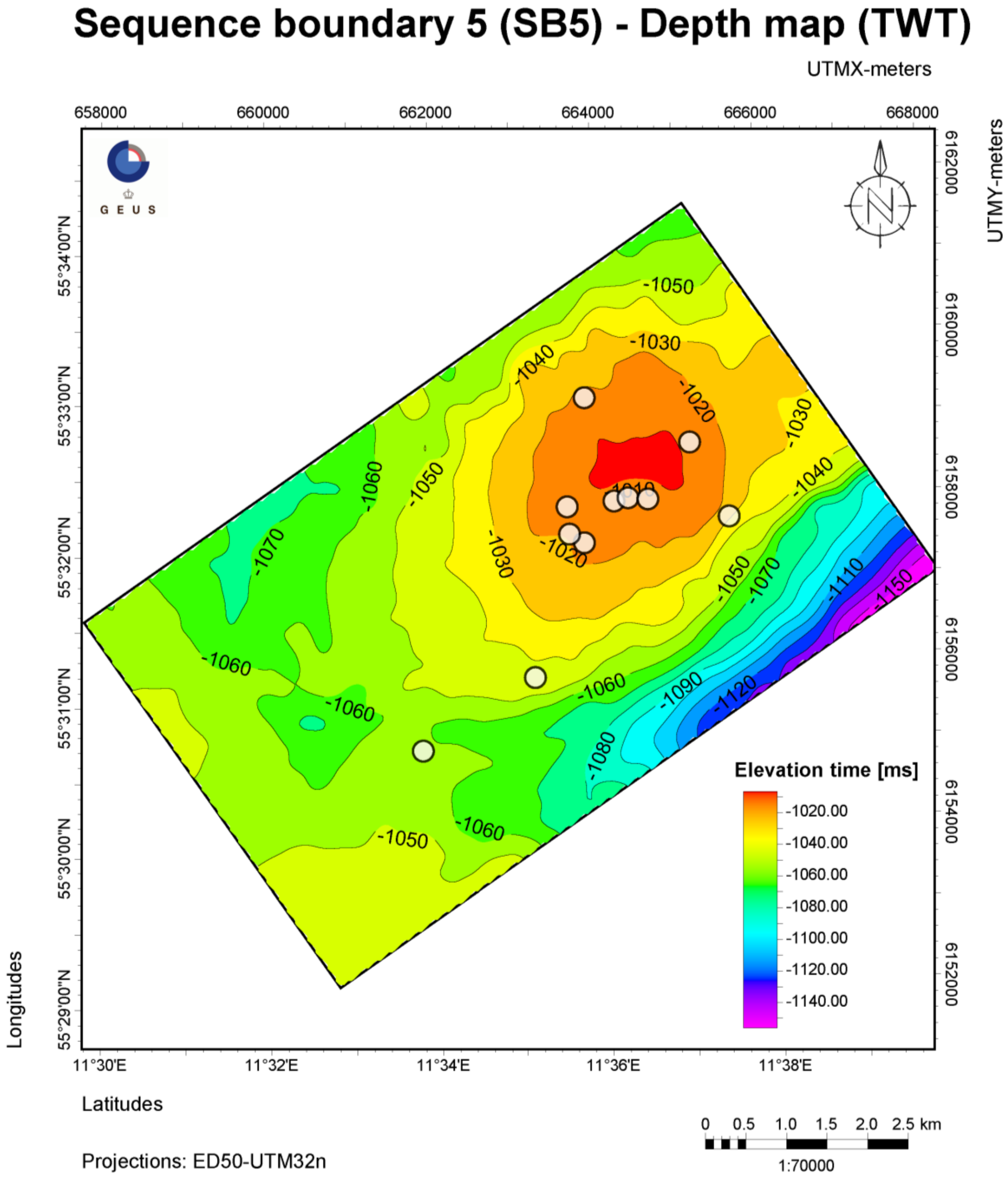

Fig. 25. Sequence boundary 5 – SB5 – time-structural map in two-way travel time (milliseconds).

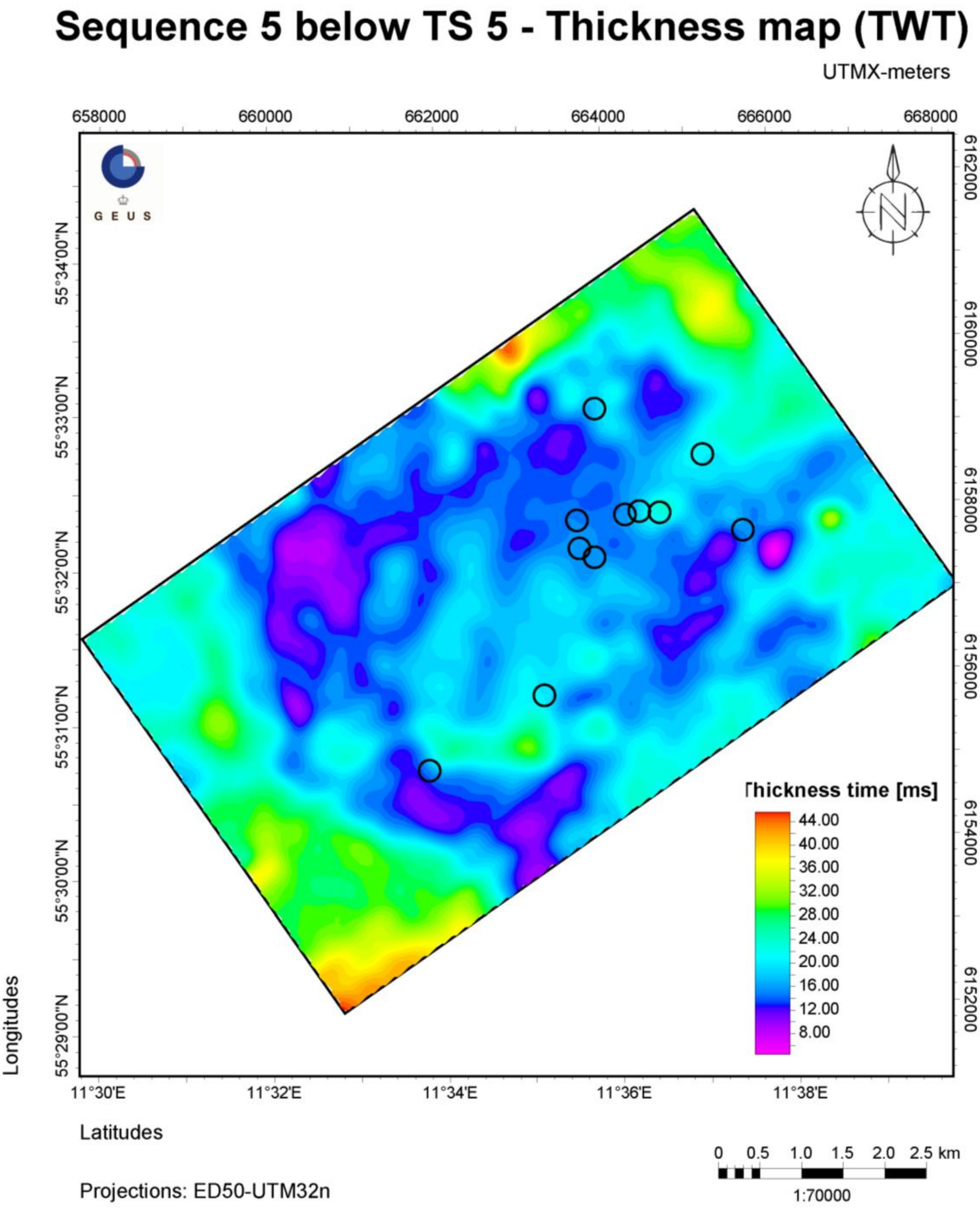

Fig. 26. Map showing the time thicknesses between the TS5 and SB5 surfaces in two-way travel time (milliseconds).

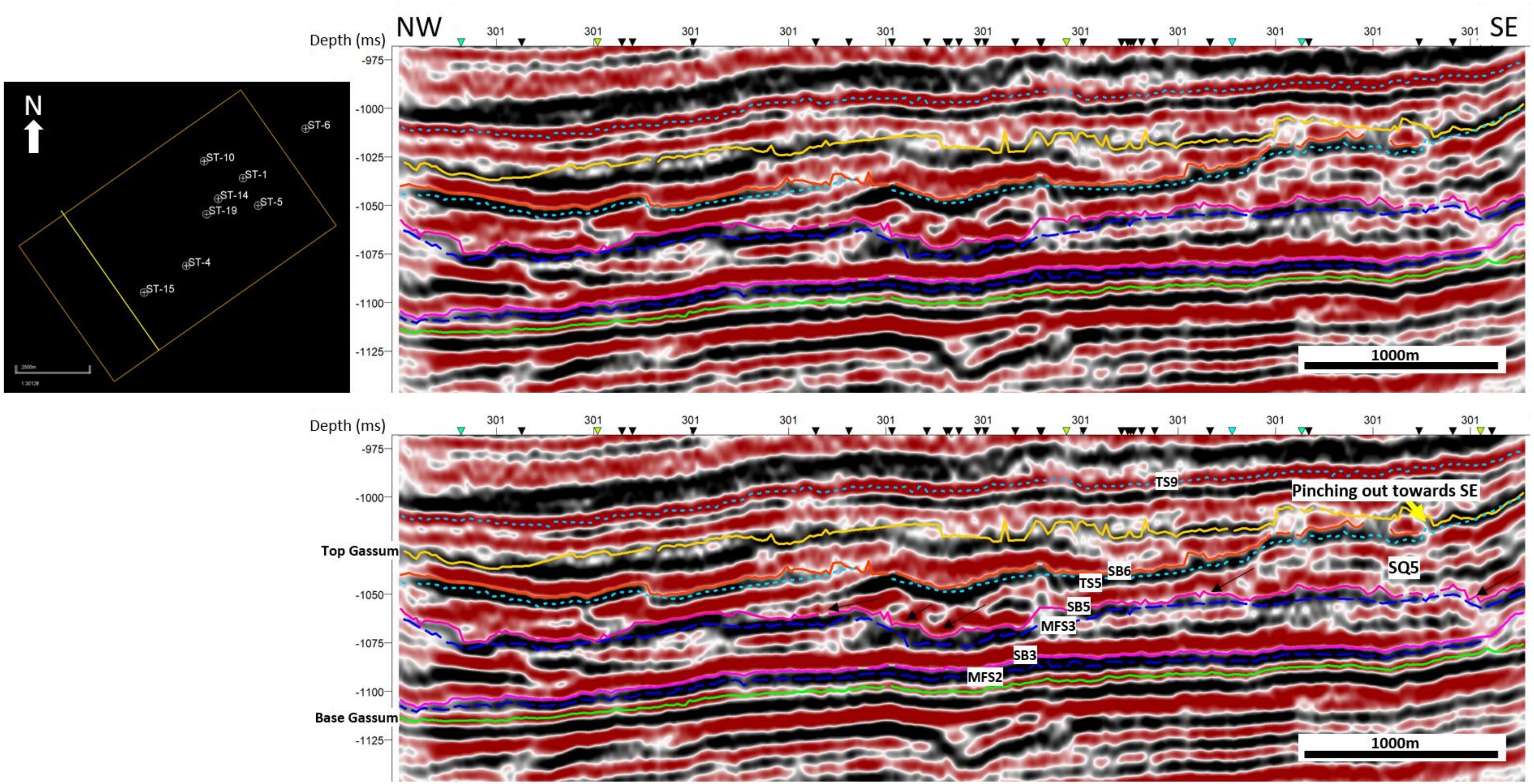

Fig. 27. NW–SE trending seismic section (XLine 301) crossing through the southern corner of the 3D survey where SQ5 is especially thick. Within the sequence, reflectors in some places appear to show NW-ward directed downlap onto SB5 (examples marked with arrows), and overall, the sequence becomes thinner from SE towards NW. This is interpreted to reflect overall LST progradation towards the NW. Also note the pinching out of the SB6–Top Gassum interval to the far SE. Depth is in two-way travel time (milliseconds). Shown with a vertical exaggeration of 10.

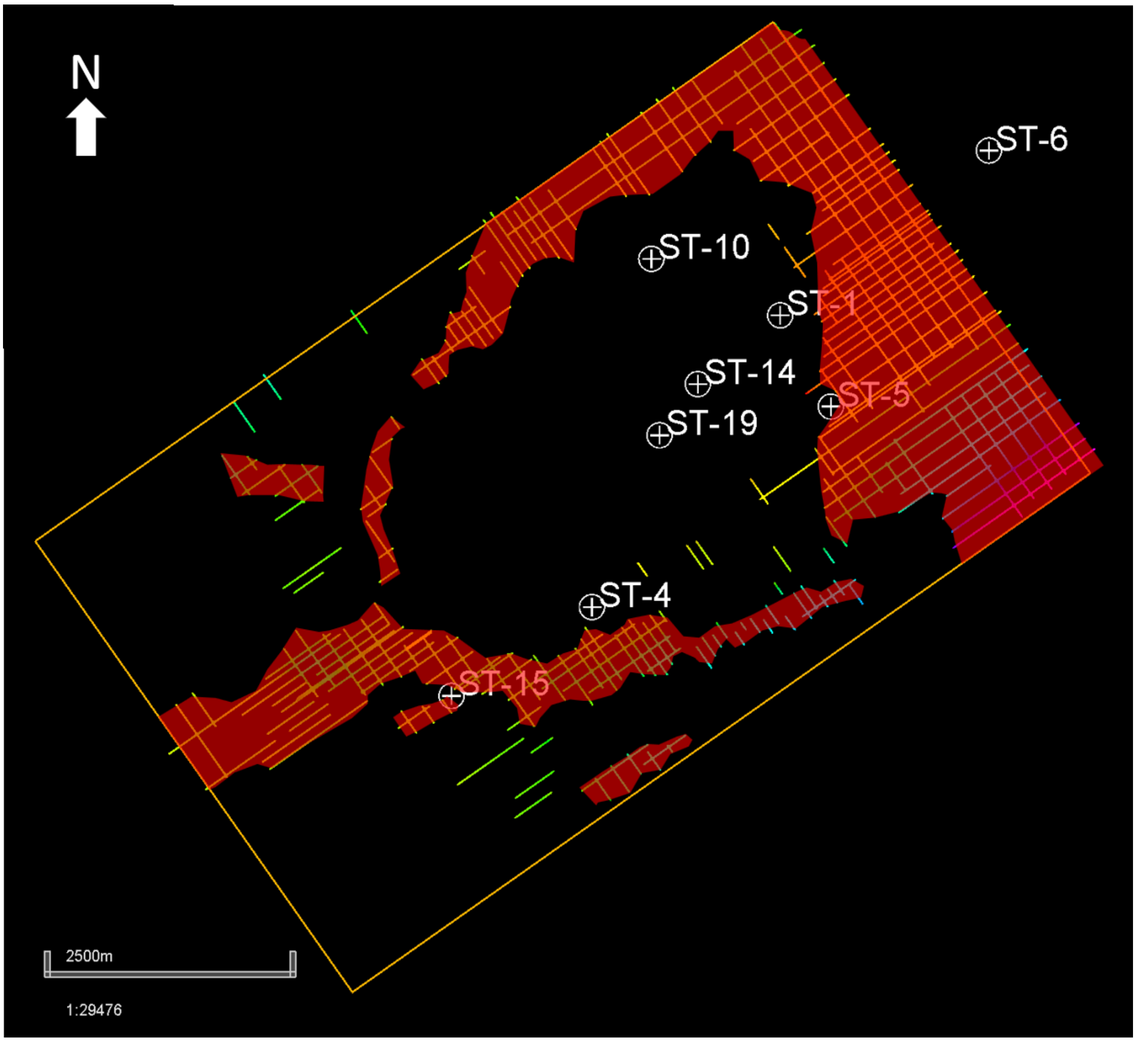

Fig. 28. Map showing areas of truncation (red coloured) based on a rough mapping of where the interpreted SB5 horizon is seen to show marked truncation on mapped seismic sections.

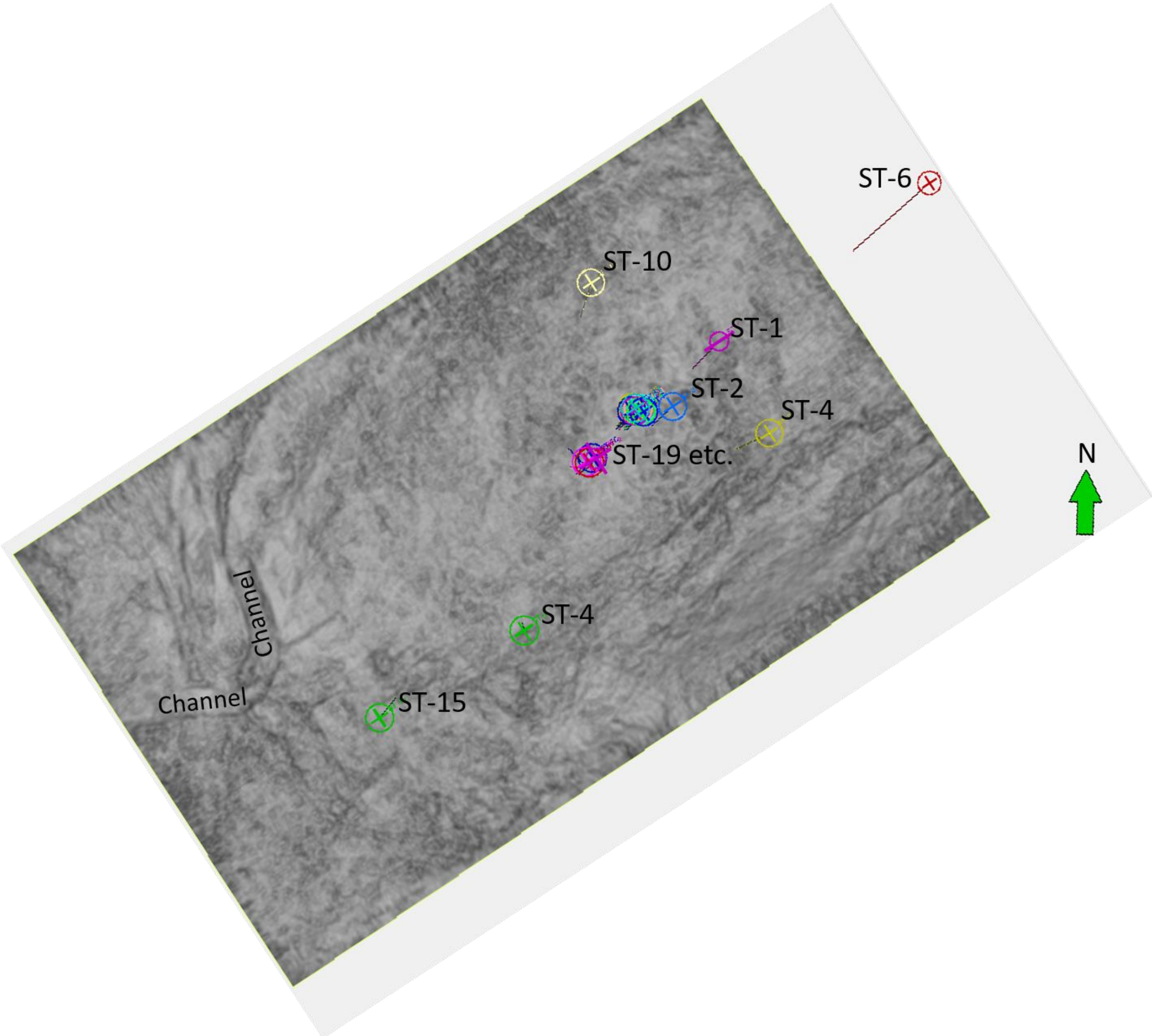

Fig. 29. Amplitude map constructed for a time depth of 1048ms (TWT). The map reveals channels in the western part of 3D survey area.

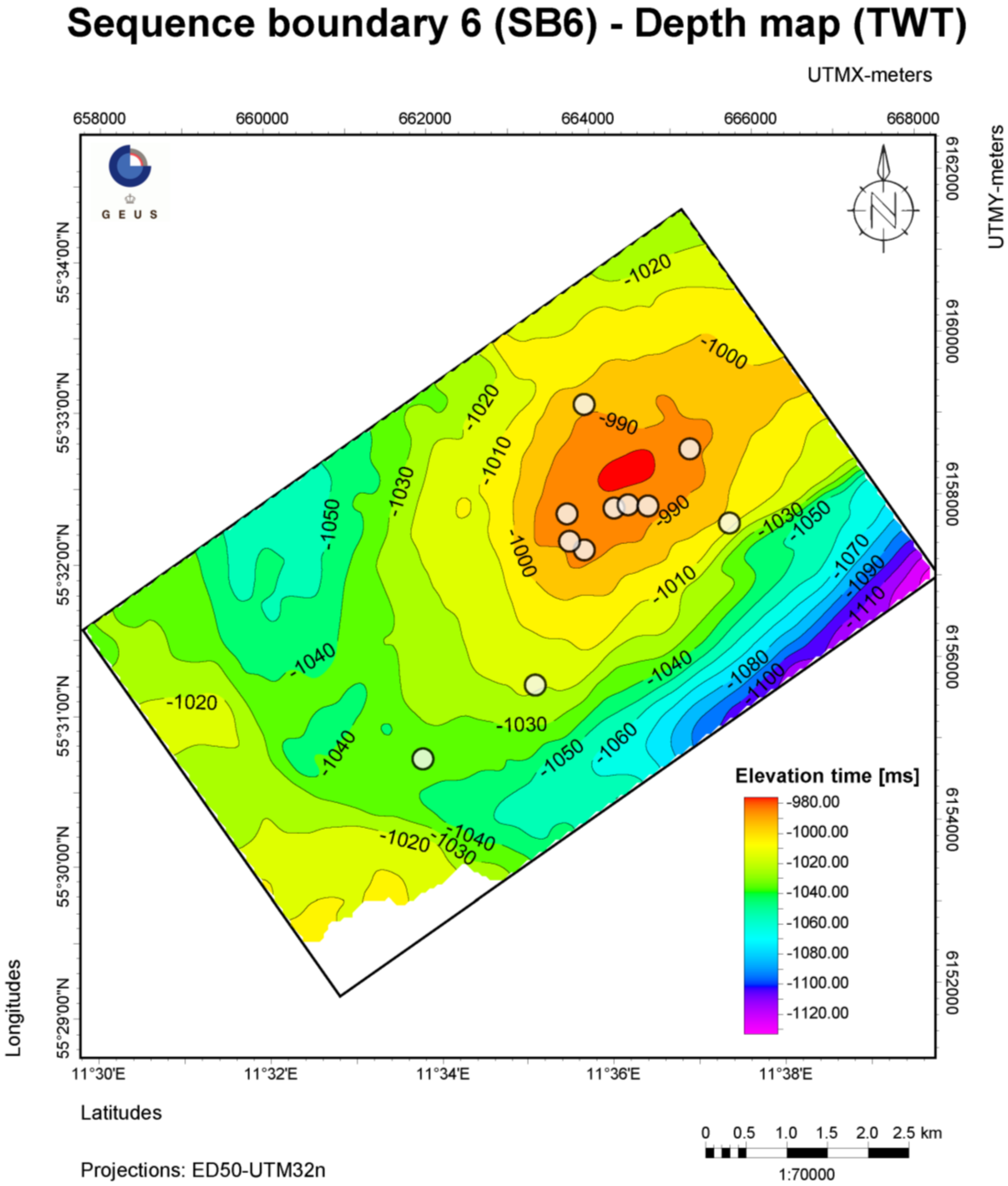

Fig. 30. Sequence boundary 6 – SB6 – time-structural map in two-way travel time (milliseconds).

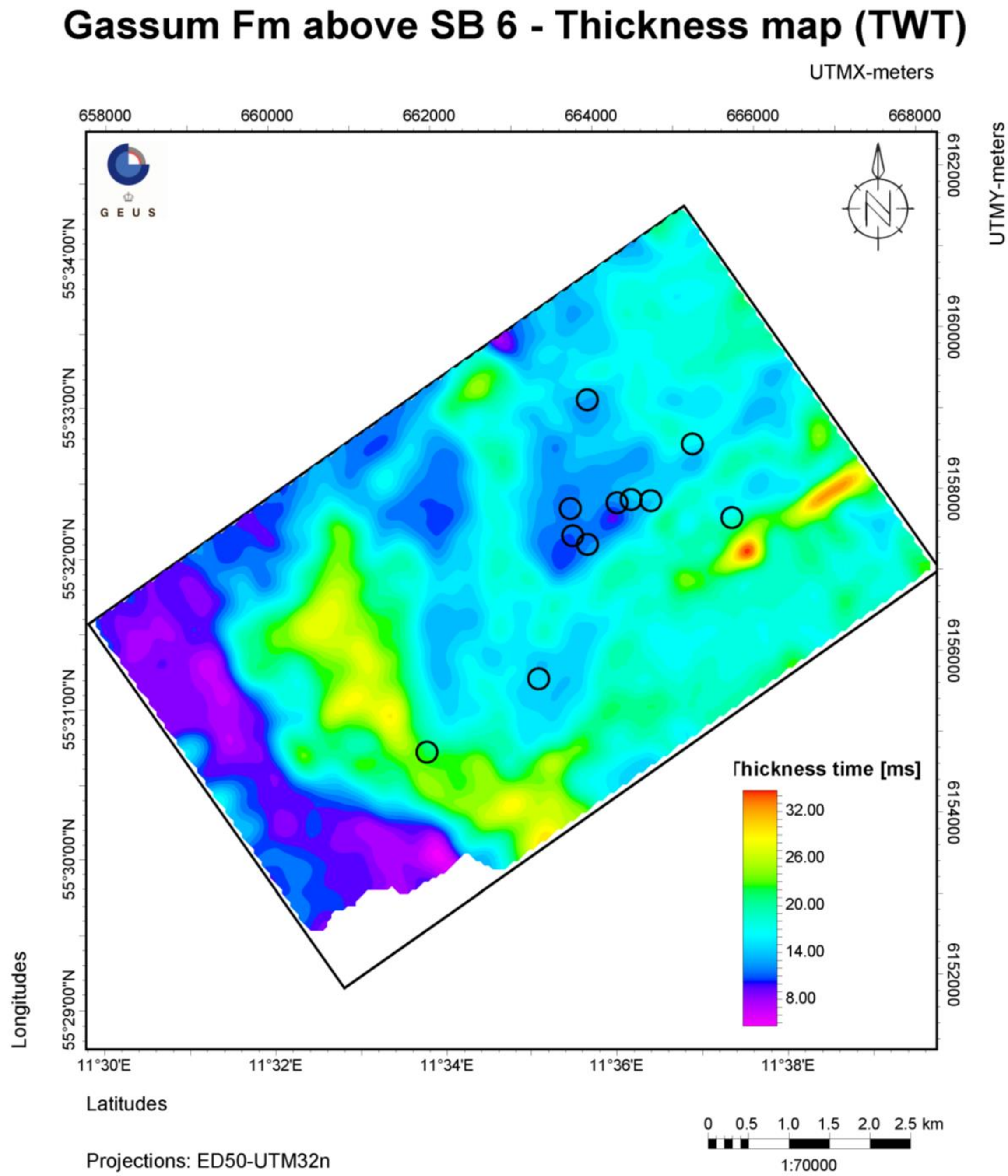

Fig. 31. Map showing the time thicknesses between Top Gassum and SB6 surfaces in two-way travel time (milliseconds).

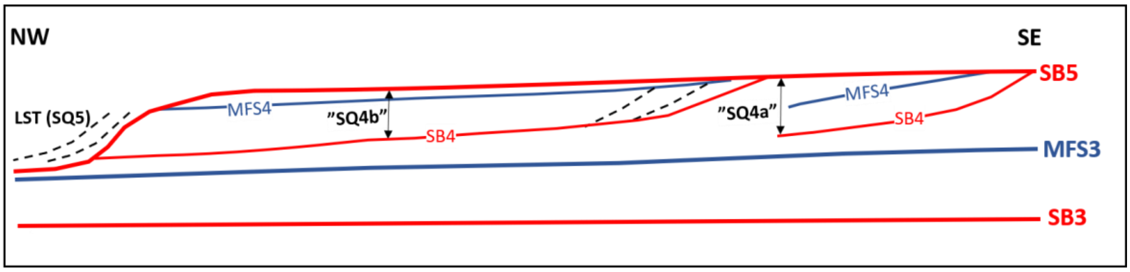

Fig. 32. Conceptual model suggesting that the two progradational events towards NW, marked as “SQ4a” and “SQ4b” of Sequence 4, represent higher-order relative sea-level oscillations relatively to (and during) a long-lasting overall relative sea-level fall which led to the formation of SB5. If so, deposits of the two progradational events should be considered as representing separate sequences.

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