DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2009/40

Structural interpretation and mapping of the Vedsted structure based on the 08VAT 2D seismic survey

Report to Vattenfall

Claus Andersen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

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Introduction

The present report comprises structural interpretation and mapping of the Vattenfall 2D seismic survey acquired autumn 2008 (08VAT) in the Vedsted/Birkelse area (Northern Jutland). The background for the seismic survey is Vattenfall's plans to establish a full-scale acquifer demonstration plant for CO_2 capture and storage close to Nordjyllandsværket in the vicinity of Aalborg.
The low relief domal Vedsted structure north-west of Aalborg has been identified as a potential storage site (Frykman et al. (2008). Old hydrocarbon exploration wells from the 1950's (Vedsted-1 and Haldager-1) have demonstrated the presence of several sandstone reservoir intervals at depths of 1200 – 2000 m and several hundred meters thick claystone intervals providing top seals. However, the existing seismic database in the area is of inferior quality largely consisting of an open grid of analog single-fold data. The aim of the seismic project was therefore to provide a modern seismic database, which enables enhanced mapping reliability.

The main objective of the structural interpretation and mapping based on the new seismic data is primarily to confirm the presence and size of structural 4-way dip closure and thickness variations of the primary reservoir of the Upper Triassic – Lower Jurassic Gassum Formation and the secondary reservoirs in the Middle Jurassic Haldager Sand and Upper Triassic Skagerrak Formation. In addition identification and mapping of faults, which potentially may breach seals, is an important issue.

The revised maps of the present study are used as input for an updated injection simulation (Frykman, 2009). Further, they form the basis for planning of 3D seismic acquisition in the crestal part of the Vedsted structure.

Database and methods

Data

The 2D seismic database comprises 24 individual lines totalling about 220 line kilometres acquired and processed on behalf of Vattenfall by the German contractor DMT during the authum of 2008. The layout of the vibroseis survey is shown in fig. 1. The line density is varying with the highest density around Birkelse near the expected apex of the Vedsted structure. A single line was recorded south of Limfjorden west of Aalborg in order to obtain a regional structural overview.
Four processed versions of the data are available and loaded on the GEUS Landmark interpretation system. They are: DMO stacks, final migration and pre-stack depth migration (PSDM) both in time and depth domain. The polarity convention used is standard (american) SEG, meaning that a peak represents an increase in acoustic impedance.
The data are generally of good quality and represents a marked quality uplift compared to the old data. However, line segments in the north-east and in the Haldager area (fig. 2) are of poor resolution, reflector continuity and misties at Gassum Formation level. This is most likely caused by a combination of soft soils, 2-D effects caused by strong dips and complex faulted geology.

The two old exploration wells (Vedsted-1 and Haldager-1) are both located outside the seismic lines. The offsets to the nearest line are 150 m and 250 m, respectively. Vedsted-1 TD'ed at 2068 m TVDSS in the uppermost Skagerrak Formation and is without check shot survey. In contrast, a check shot survey is available in Haldager -1, however, the well is shallower with TD at 1519 m TVDSS in Fjerritslev Formation F-III Member. This prohibits a direct seismic tie to the main target of the Gassum Formation.

Interpretation

Following 6 horizons have been interpreted both on PSDM time and depth sections and tied to the formation picks in the Haldager well when possible. The markers are

- Base Chalk Group
- Top Frederikhavn Formation
- Top Haldager Sand Formation
- Base Haldager Sand Formation – Mid Cimmerian Unconformity (MCU)
- Intra Fjerritlev F-III marker (sequence boundary SB15, Nielsen 2005) penetrated close to TD in Haldager-1
- Near Top Gassum Formation

In addition a Near Top Skagerrak Formation and an uncorrelated Intra-Triassic marker have been picked when data quality allows. All interpreted horizons have been digitally transferred to Vattenfall.

The rather loose terms Near Top Gassum and Skagerrak Formations have been used as no direct well ties are possible due to lack of recorded time-depth relationships in the Vedsted-1 well. The Near Top Gassum horizon has been picked in a generally high amplitude and continuous trough at 1330 ms corresponding to about 1840 m on PSDM depth section 08VAT22 at SP 1050 about 150m west of the well location. The top of the upper sandstone interval of the Gassum Formation in the well is drilled at 1744 m TVDSS.
The Near Top Skagerrak Formation is picked in a continuous and mapable trough on the depth sections corresponding to a depth of 2065 m in the well. The formation pick in the well is 2032 m TVDSS.

Mapping procedure

Following depth structure maps have been generated directly from the interpretations on the PSDM depth sections:

- Base Chalk Group
- Top Haldager Sand Formation
- Base Haldager Sand Formation
- Near Top Gassum Formation
- Near Top Skagerrak Formation

Draft structure map was first prepared manually in order to establish the most likely fault trace pattern. Fault traces and horizons were subsequently imported to Z-map Plus for final gridding. The point gridding algorithm with a search radius of 10 km and a grid point spacing of 100 m was used. Areas with poor data quality have been blanked in the final display version.

Isochore maps of Haldager Sand Fm and the ‘Gassum’ interval have been prepared with a contour interval of 25 m. The latter is the interval bounded by the Near Top Gassum Fm and the Near Top Skagerrak Fm seismic horizons. The maps were generated by subtraction of the interpreted bounding horizons in Seisworks and subsequent gridding in Z-map Plus.

Interpretation results

Seismic key sections

The structural style in the survey area is illustrated by a selection of key seismic PSDM depth sections in figs. 4-9. Locations are shown in fig. 3.
Line 08VAT22 (fig.4) is a longitudinal section along the axis of the Vedsted structure displaying a gentle anticline with the apex located about 2 km south the well location close to SP 1050. Thickness variations are minor and mostly confined to the lower part of the Fjerritslev Formation showing a northward increase. A number of small extensional faults are identified at Base Chalk level but seem to sole out in the Lower Cretaceous.
Fig. 5 is a composite section north of the Vedsted structure composed of 3 line segments. The most conspicuous structural feature is a growth fault in the west affecting all interpreted levels. To the north-east structural roll-over is recorded in the heavily faulted post-Haldager Sand Fm section. The section below is poorly imaged and not interpreted. This feature, informally termed the 'Pandrup structure' is not recognised on the old seismic database.
Figs. 6-8 are dip-sections across the Vedsted structure from north to south. The growth fault described above delineates the structure to the west and shows decreasing displacements to the south. Here it only affects the pre-Mid Jurassic section. The fault soles out in the Triassic, possibly in evaporates (e.g. Oddesund Formation salt as known from other wells in the region) (fig. 8, 08VAT08). The NW-SE trending basement-attached Haldager fault zone to the northeast of the structure is displayed in fig. 7 (08VAT03). The data quality is poor at Gassum Fm level on the footwall block. However, reflectivity reappears in the deep section.
Fig. 9 (08VAT10) is a SW-NE oriented section passing close to Haldager-1. The well is located on the hanging wall of the poorly imaged and complex Haldager fault zone.

The structural development of the Vedsted structure is illustrated by simple flattening of line 08VAT08 across the southern part at Base Chalk and Base Haldager, respectively (figs. 10 & 11). The flattened sections indicate only insignificant structural growth during Early Cretaceous and Late Jurassic deposition (fig. 10). The major structural growth took place during deposition of the lower part of the Fjerritslev Formation (fig. 11). The upper part of the Triassic (Skagerrak Fm) has a uniform thickness.

Structure and isochore maps

The Base Chalk Group depth structure map (fig. 12) displays a NNW-SSE trending anticline with small isolated culminations at a depth of about 400 m on the hangingwall of the Haldager fault zone in the east. The surface is cut by the above described antithetic normal fault in the north-west. Minor extensional faults with less than 20 m displacements occur in the crestal part of the anticline. They seem to sole out in Lower Cretaceous section below.

The formation of the anticline is traditionally believed to be the result of Late Cretaceous compressional movements in the Sorgenfrei-Tornquist Zone. Basal onlaps are recognised on the flanks of the anticline suggesting early Late Cretaceous growth.

The mapped Top and Base of the Haldager Sand Fm are shown in figs. 13 & 14. The 4-way dip-closed Vedsted structure at Top Haldager Sand Fm level is separated from the northern 'Pandrup structure' by a saddle at 1325 m. The mapped crest at 1090 m is located about 2 km south of the Vedsted-1 well location and the spillpoint to the south-east in the direction of the Haldager-1 well is at 1175 m on line 08VAT08. Compared to Top Haldager Sand Fm a number of minor faults have been mapped to cut the Base Haldager Sand Fm surface in the crestal area.
The mapped isochores of the Haldager Sand Fm (fig. 15) shows a gradual thickening of the formation on the south-eastern flank of the structure. This is in agreement with drilled thicknesses increasing from 75 m in Vedsted-1 to 155 m in Haldager-1. A high amplitude, partly hummocky internal reflection pattern is observed near the Haldager-1 well on line 08VAT10 (fig. 9) suggesting the presence of stacked channels.

The Near Top Gassum Formation and Near Top Skagerrak Formation depth maps are displayed as fig. 16 & 17 both with a contour interval of 50 m. The structurally closed area is considerably larger than at Haldager Sand Fm level. The mapped apex of the Vedsted structure at Near Top Gassum Fm level is at 1780 m about 2 km south of the well. The mapped spillpoint at 2000 m west of the growth fault is poorly defined. The seismically mapped 'Gassum' isochores (fig.18) shows a general increase in thickness of the interval bounded by the Near Top Gassum Fm and Near Top Skagerrak Fm horizons on the flanks of the structure, most markedly on the eastern flank on the hangingwall of the Haldager fault zone. The drilled gross thickness of the Gassum Formation including interbedded Fjerritslev Fm mudstones in Vedsted-1 is 288 m. This value should be compared with mapped isochore of 225 m. The internal reflection pattern is parallel to slightly divergent on the flanks with a few indications of basal onlap.

Seismic velocities

Due to lack of pre-existing knowledge on the acoustic velocity field based on 'hard' well data the depth maps were generated directly from the interpretation on PSDM depth sections. This procedure seems justified by the fact that only small misties at line intersections are observed in most of the survey area. This suggests that a careful velocity picking job was carried out by the processing contractor.
An example of the migration velocity field is shown in fig. 19. On this line (08VAT03) crossing the central part of the Vedsted structure interval velocities above 3000 m/sec are found in the basal onlapping part of the Chalk interval on the flanks. Below the expected velocity inversion at Base Chalk the interval velocities increase gradually with depth with only minor random noise in the siliciclastic section.
The average velocities from surface to Near Top Gassum Fm were tested by generation of an average velocity map by division of the Near Top Gassum Fm depth grid with the time grid (fig. 20). The resulting velocity field is relatively uniform in the crestal part with calcu-

lated values at about 2800 m/sec gradually increasing to about 3200 m/sec on the lower flanks. An average velocity of 2800 m/sec based on migration velocities is about 5% higher than calculated directly from the formation pick in Vedsted and the TWT value on Near Top Gassum Fm reflector close to the well location. This suggests a slight overestimation of the velocities in the section below the Haldager Sand Fm level. In order to correct for the misfit between the mapped depths of the Near Top Gassum Formation to the ‘true’ Top Gassum Formation a constant upward depth shift can be applied assuming a near ‘layer cake geology’.

Summary and recommendations

The 08VAT 2D seismic survey represents a major increase of data and quality uplift compared to the pre-existing seismic database and allows increased reliability on structural maps of the target intervals at the Vedsted structure. The presence of structural closures has been confirmed at top of the reservoir intervals at Haldager Sand, Gassum and Skagerrak Fm levels.
At Top Haldager Sand a small 4-way dip closure with the apex at 1090 m some 2 km south of the Vedsted-1 well location and a structural spillpoint to the south-east at 1175 m has been mapped.
At Near Top Gassum Formation level the structure is considerably larger. The mapped apex is at 1780 m and the structural spillpoint is at 2000 m located on the footwall of a growth fault to the west. The mapped surface at the well location is about 90 m deeper than the top of the upper Gassum sandstone interval recorded in the well. This is due to a combination of poor seismic tie and possibly to too high migration velocities applied on the PSDM data. To overcome this misfit an upward constant shift of 90 m can be used for correction to ‘true’ Top Gassum Formation across the survey area.

The spillpoint at Near Top Gassum level to the west is poorly constrained. It is therefore recommended to extend the planned 3D survey over crestal area with up to 4 2D lines in a westward direction in order to get better control on the fault zone and definition of the spillpoint.

References

Frykman, P., Bech, N., Nielsen, C. M., Vangkilde-Pedersen, T., Bidstrup, T., Kristensen, L. & Dalhoff, F. 2008: Preliminary CO_2 storage capacity estimation for the Vedsted Structure. Geological model and reservoir simulation, version 0. Danmark og Grønlands Geologiske Undersøgelse Rapport 2008/39

Frykman, P. Preliminary report on V_1.0 model and injection simulation. Draft version, April 15, 2009-06-05

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

Figures

Survey layout

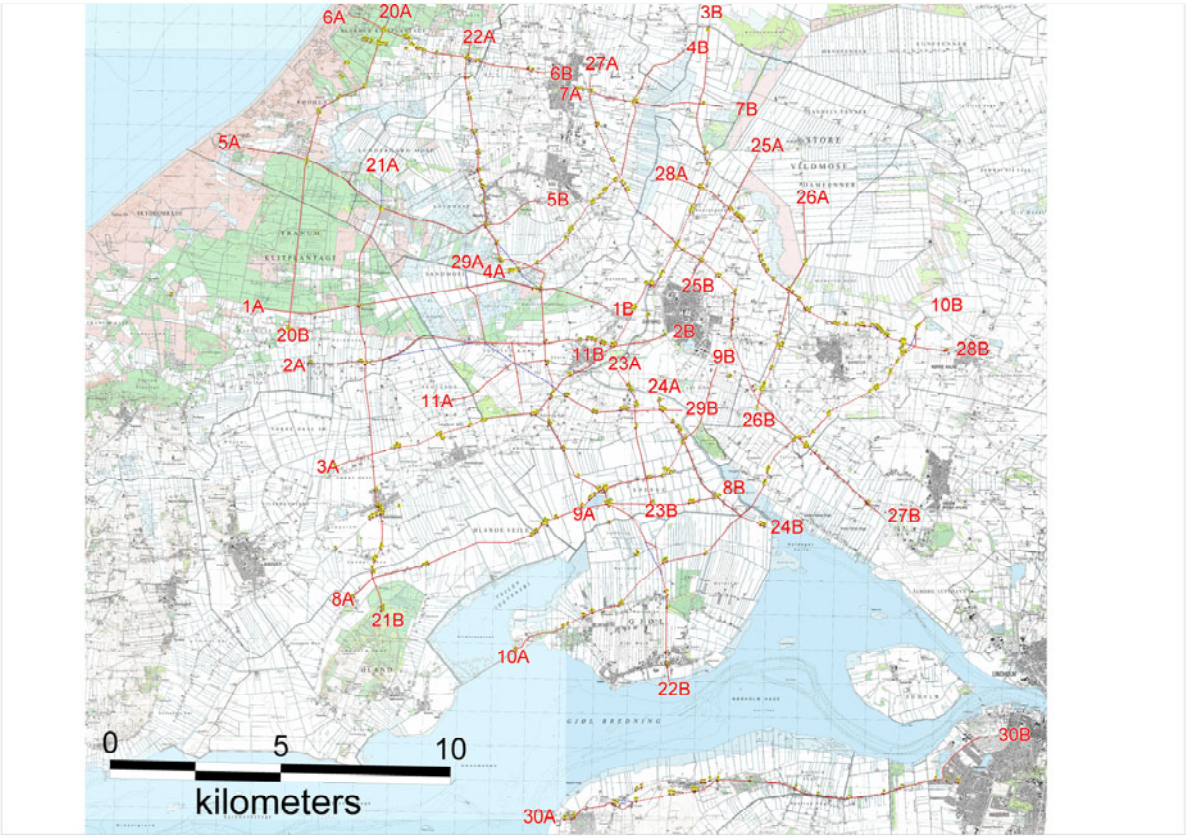

Fig. 1: Survey layout of Vattenfall 2008 2D vibroseis survey

Shot point base map

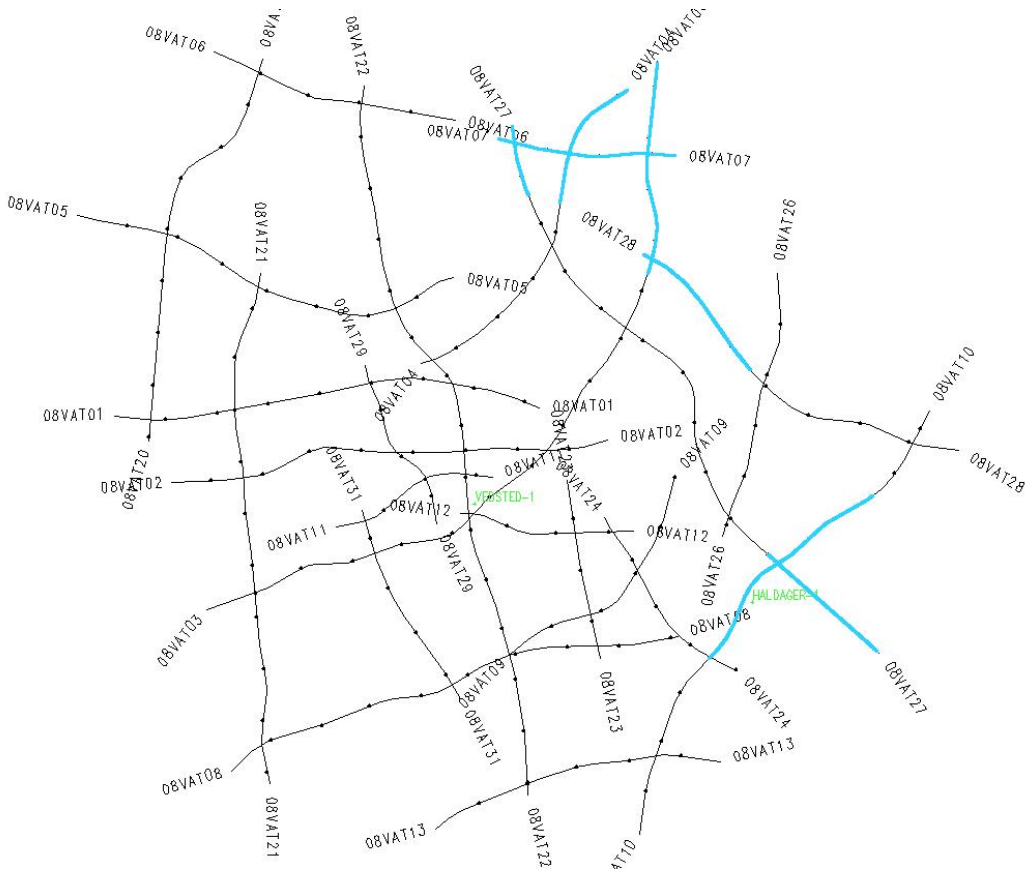

Fig. 2: Shot point base map of Vattenfall 08 2D survey with location of Vedsted-1 and Haldager-1 wells indicated. Line 08VAT30 south of Limfjorden omitted.
Light blue coloured line-segments are of poor resolution and reflector continuity at Gassum level.

Location of selected key sections

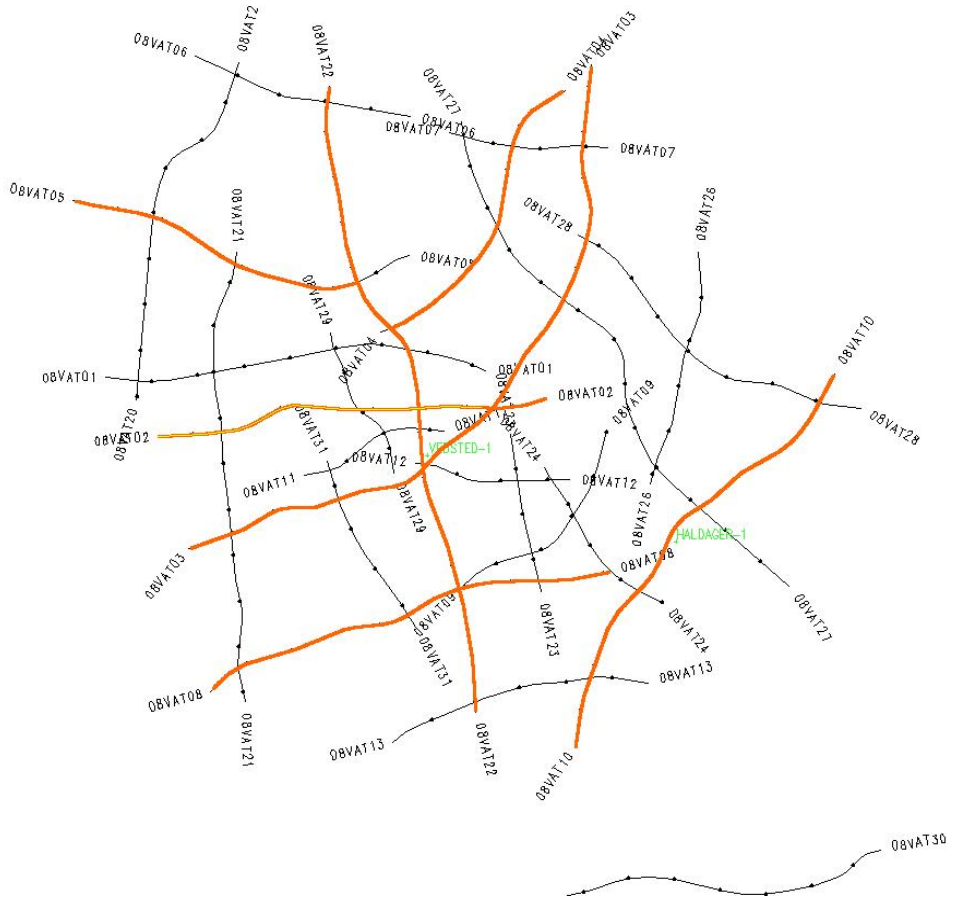

Fig. 3: Location of key PSDM depth sections shown in Figs. 4 – 9.

08VAT22 (PSDM depth section)

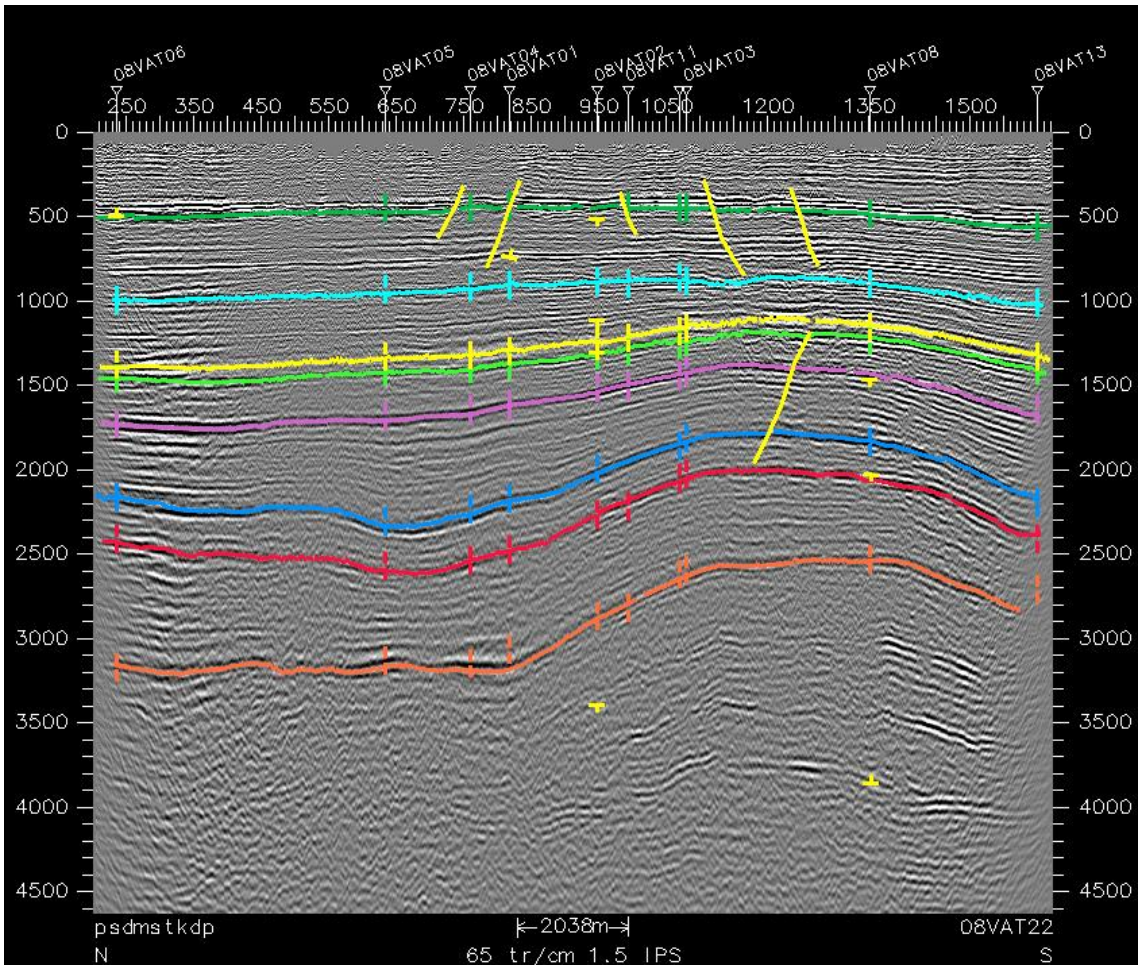

Fig. 4: N-S section along crest of Vedsted structure. Vedsted -1 well located close to SP 1050. Apex is located app. 2 km south of well.
Colour code: - Dark green: Base Chalk Group; - Light blue: Top Frederikshavn Formation, -Yellow: Top Haldager Sand Formation, -Light green: Base Haldager Sand Formation (MCU), -Purple: Intra Fjerritslev F-III Member (sequence boundary SB15 defined by Nielsen, 2005), - Blue: Near Top Gassum Formation, -Red: Near Top Skagerrak Formation, -Orange: Intra Triassic marker.
Note: minor extensional faults cut Base Chalk, but sole out in Lower Cretaceous.
The Near Top Gassum and Near Top Skagerrak seismic markers have been defined as strong continuous troughs on this line.

Composite line 08VAT05/22/04 (PSDM depth section)

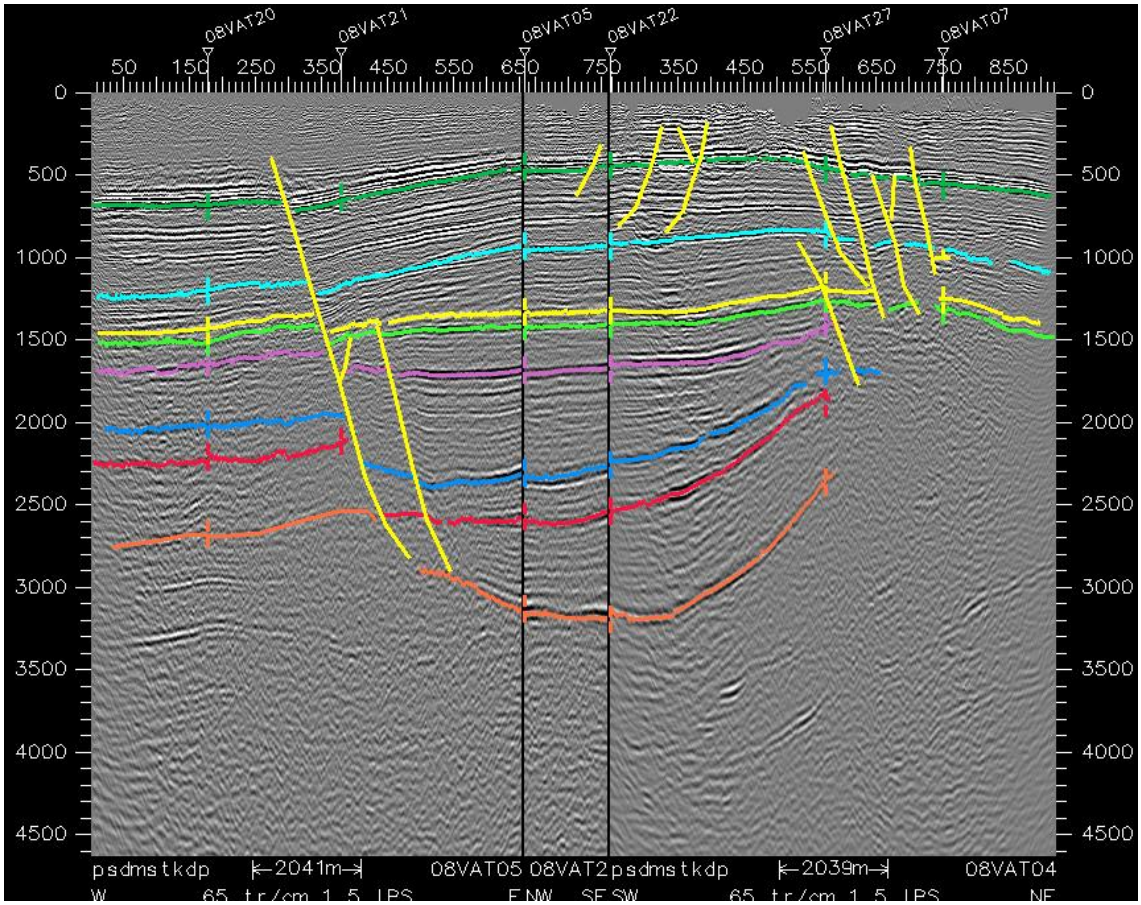

Fig. 5: Composite W-E cross-section north of Vedsted structure. Location is shown in Fig. 3.
Note: Growth fault to the west also affecting the lower part of the Chalk section and poor reflector continuity on heavily faulted 'Pandrup Structure' below Haldager Sand Fm level.
For colour code: see Fig.4.

08VAT02 (PSDM depth section)

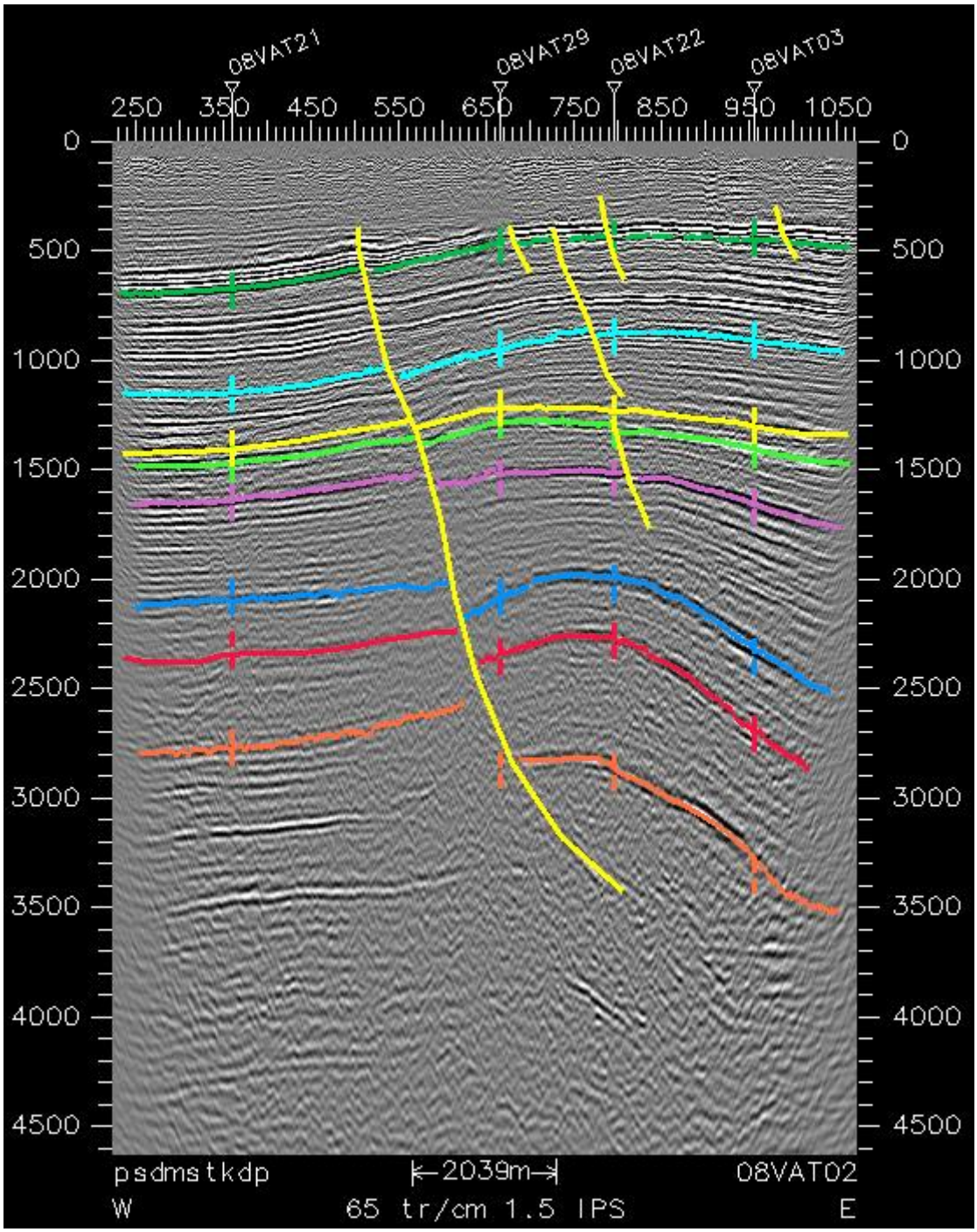

Fig. 6: Section across northern part of Vedsted Structure. Location is shown in Fig. 3.
Note: Growth fault affecting all interpreted levels soling out in the Triassic section. The structural spill-point of the structure at Near Top Gassum Fm is located close to SP 600 on the footwall of the growth fault.
For colour code: see Fig. 4.

08VAT03 (PSDM depth section)

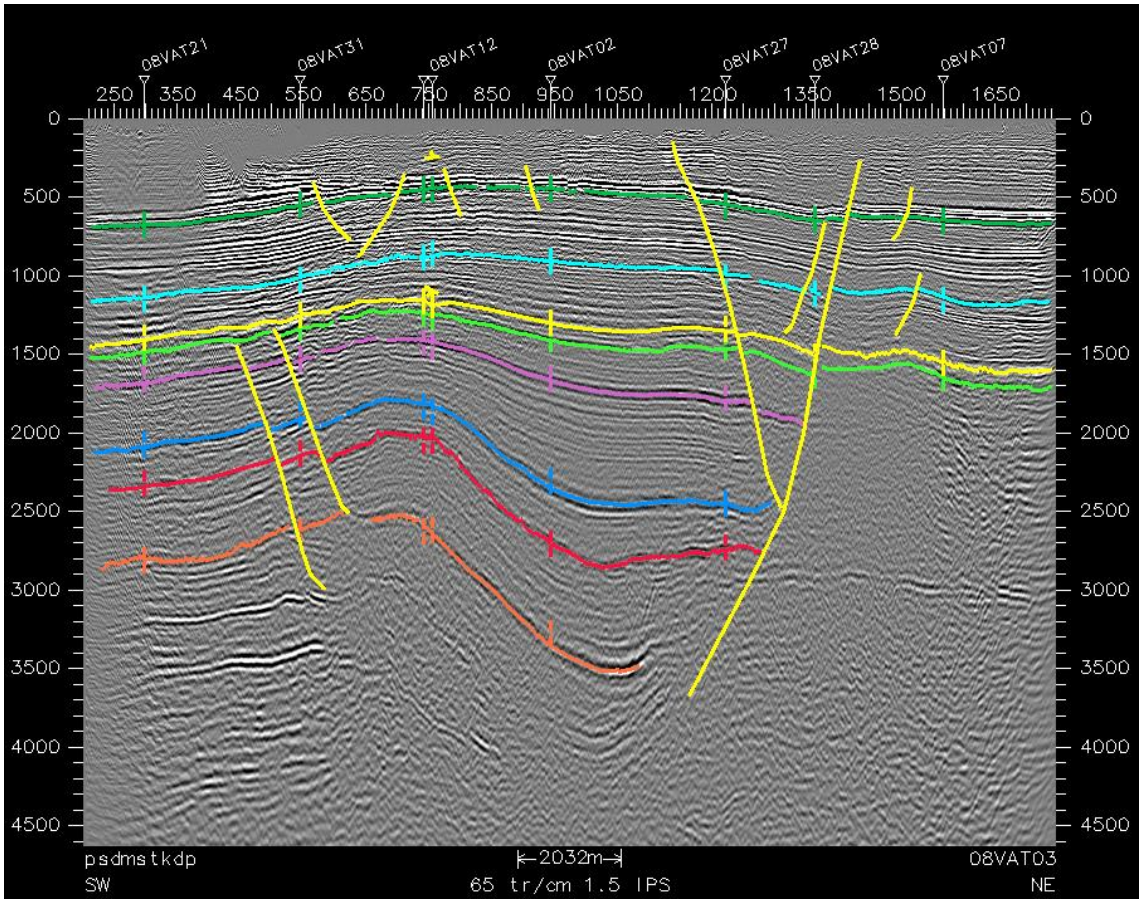

Fig. 7: Section across central part of Vedsted Structure. Location is shown in Fig. 3.
The apex of the structure is apparently offset slightly to the south-west of the Vedsted -1 well location at SP 770.
Note: Poor data north-east of basement-attached fault at Gassum Fm level. Reflectivity re-appears in the deep section below 2800 m.
For colour code: see Fig. 4.

08VAT08 (PSDM depth section)

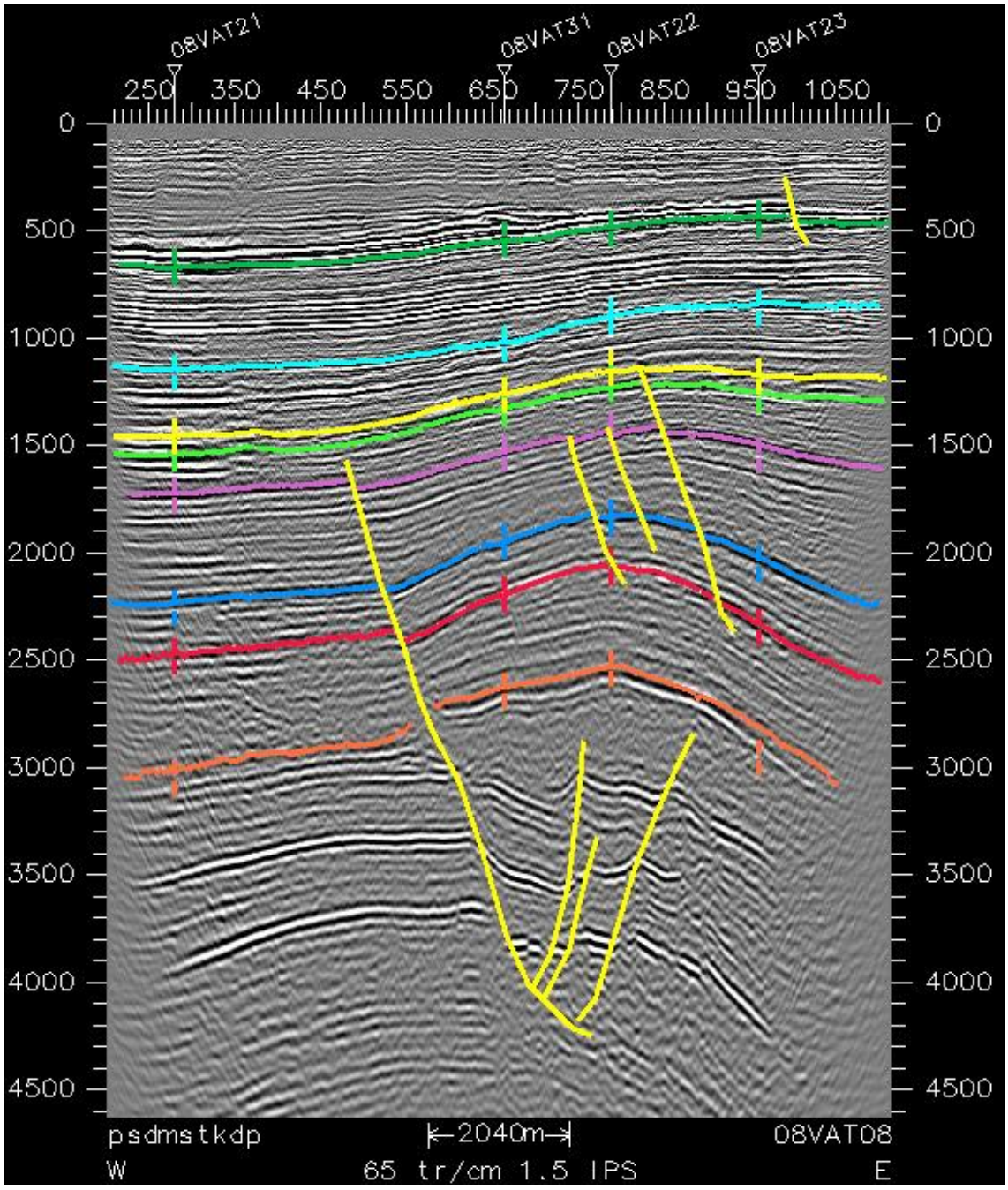

Fig. 8: Section across southern part of Vedsted structure. Location is shown in Fig. 3.
The western growth fault affects only the pre-Haldager Sand Fm section and soles out in the Triassic (evaporate?) section at app. 4000 m. Minor listric faults displace Gassum Fm level at the structural culmination.
For colour code: see Fig. 4

08VAT10 (PSDM depth section)

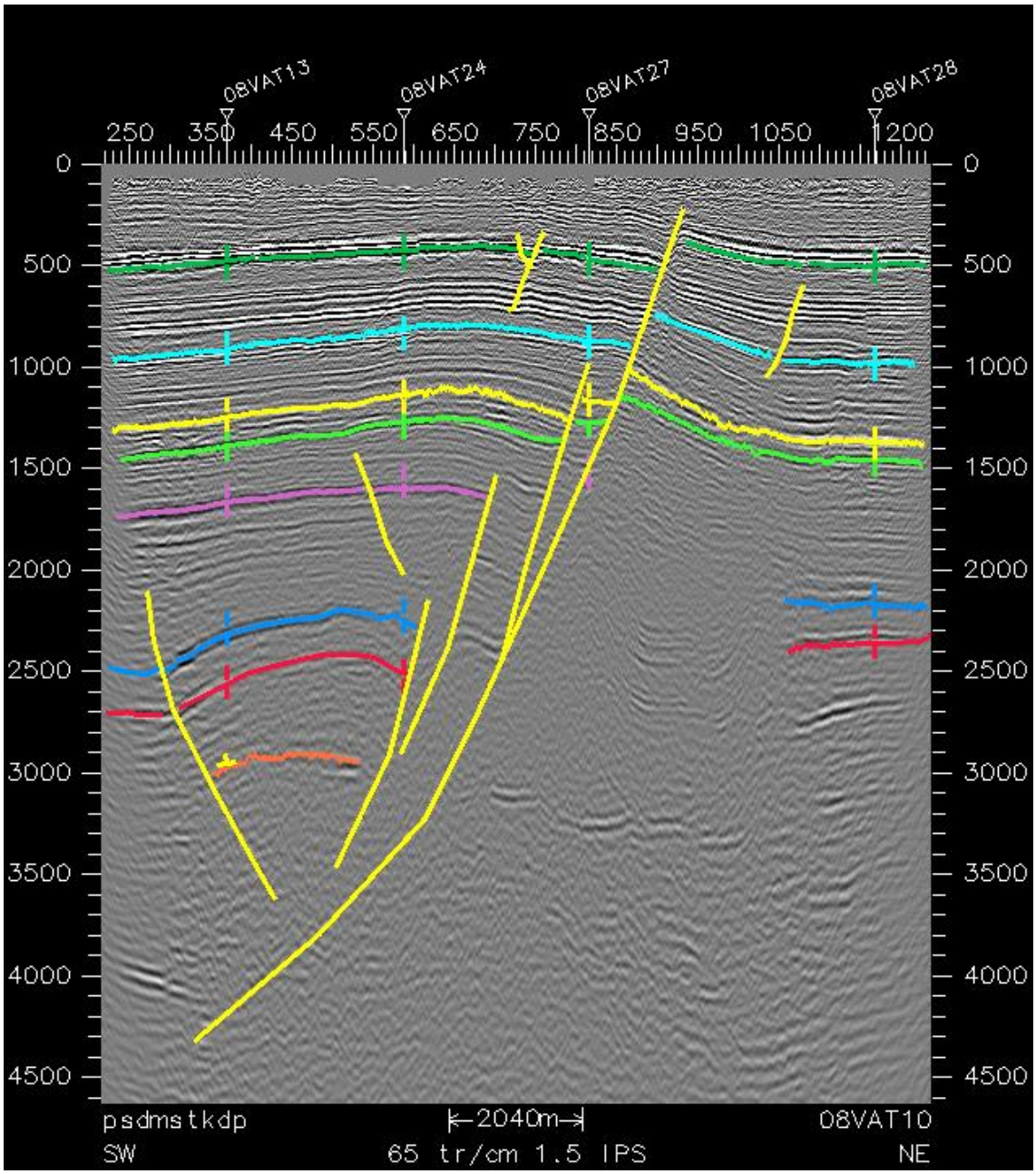

Fig. 9: SW-NE section close to the Haldager-1 well (offset south of SP 710). The location is shown in Fig. 3. The well is drilled in a complex fault zone.
Note: Poor data continuity at Gassum level at footwall NE of fault. Deep (uncorrelated) reflections are however visible.
For colour code: see Fig. 4.

08VAT08 flattened at Base Chalk Group

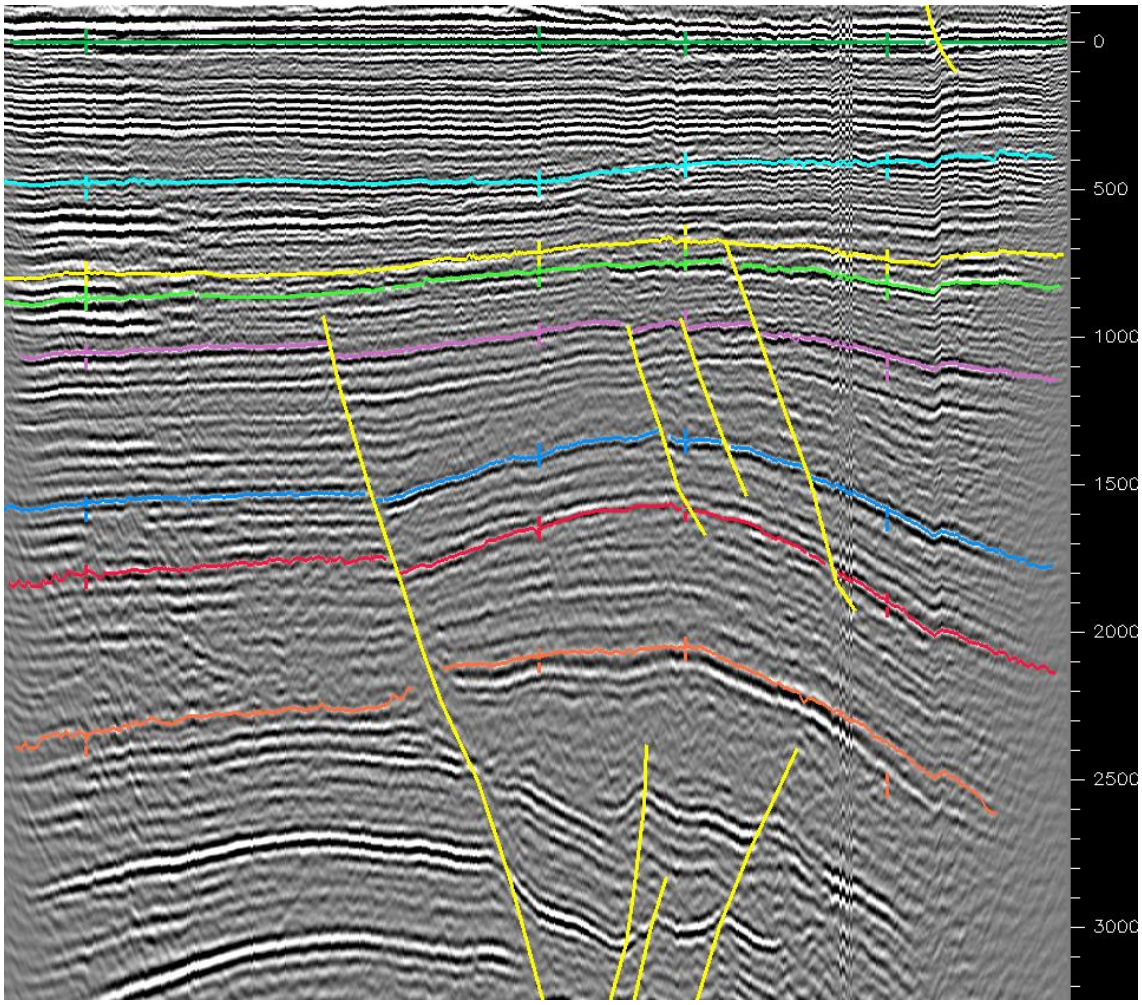

Fig. 10: Line 08VAT08 (PSDM depth section) flattened at Base Chalk. Note only insignificant structural growth during Early Cretaceous and Late Jurassic deposition (between dark green and yellow horizons).

08VAT08 flattened at Base Haldager Sand Fm

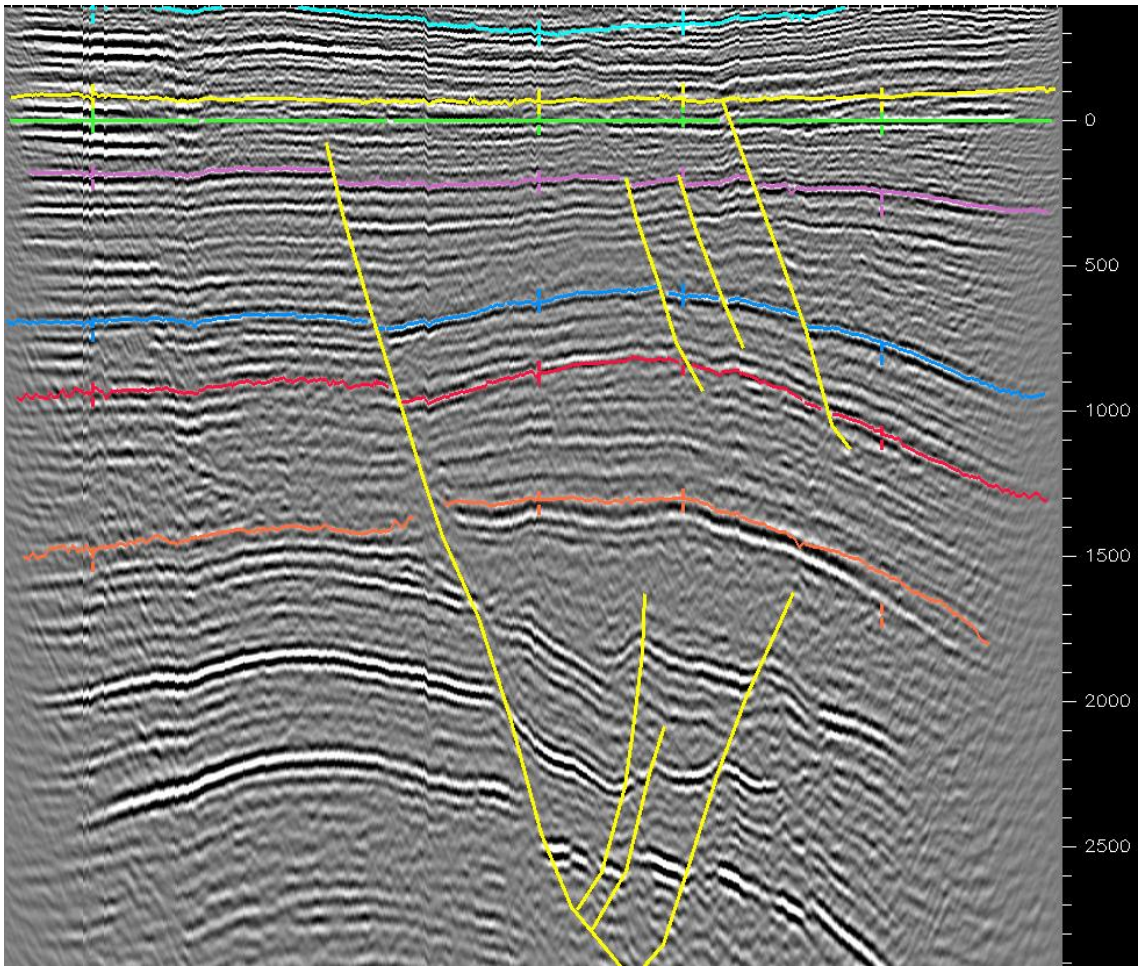

Fig. 11: Line 08VAT08 (PSDM depth section) flattened at Base Haldager Sand Fm (MCU) level.

Major structural growth took place during deposition of lower part of the Fjerritslev Formation (between purple and blue horizons). The upper part of the Triassic (between red and orange horizons) has uniform thickness.

Base Chalk Group depth map

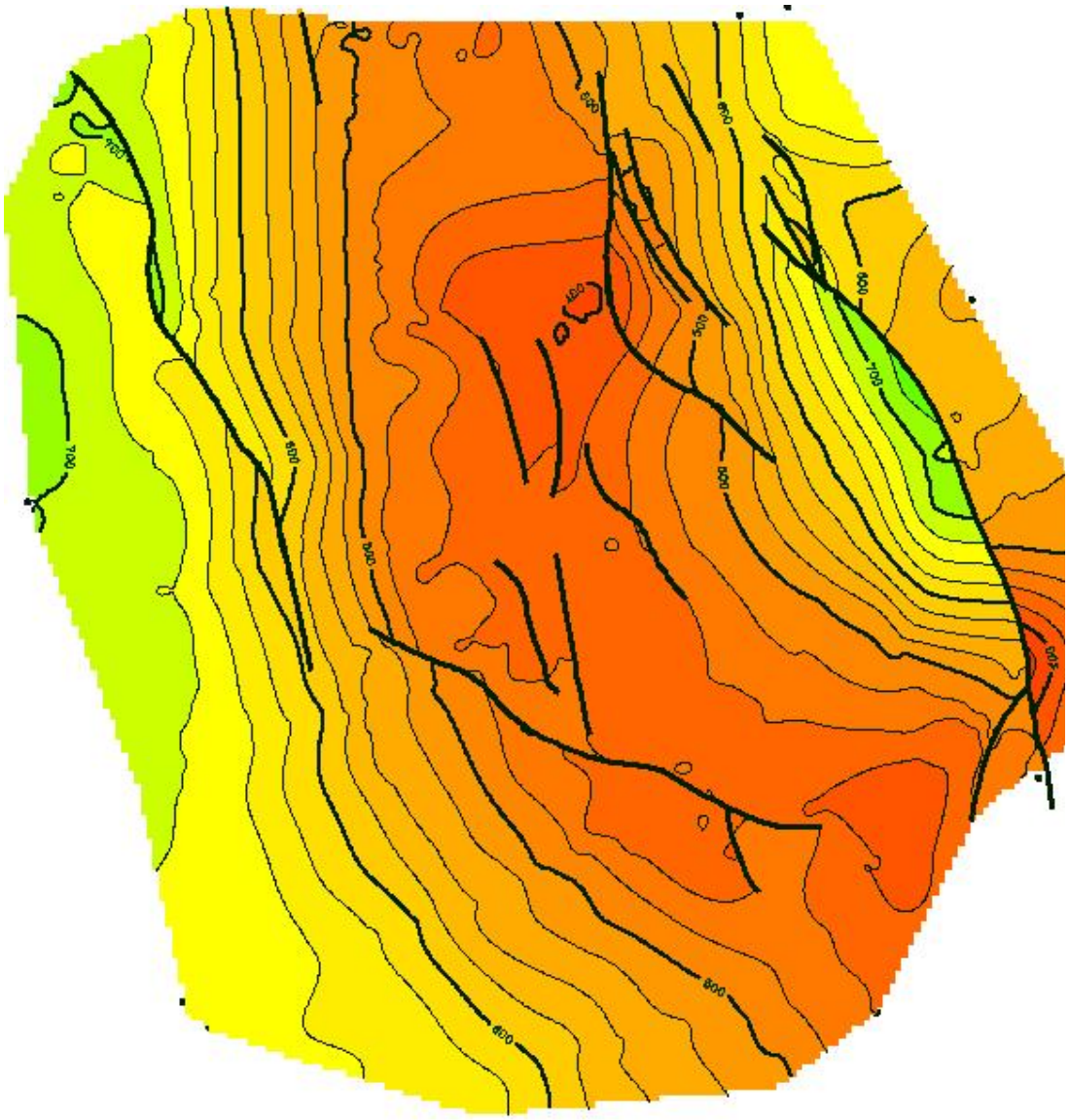

Fig. 12: Base Chalk Group depth map based on PSDM depth sections.
Contour interval: 25 m
The map displays a NNW-SSE trending low relief anticline with small isolated structural culminations. The anticline is delineated by a major normal fault to the east. A down-to-the-east antithetic growth fault cut the surface in the north-west. Minor extensional faults with less than 20 m displacement occur in the crestal parts.

Top Haldager Sand Formation depth map

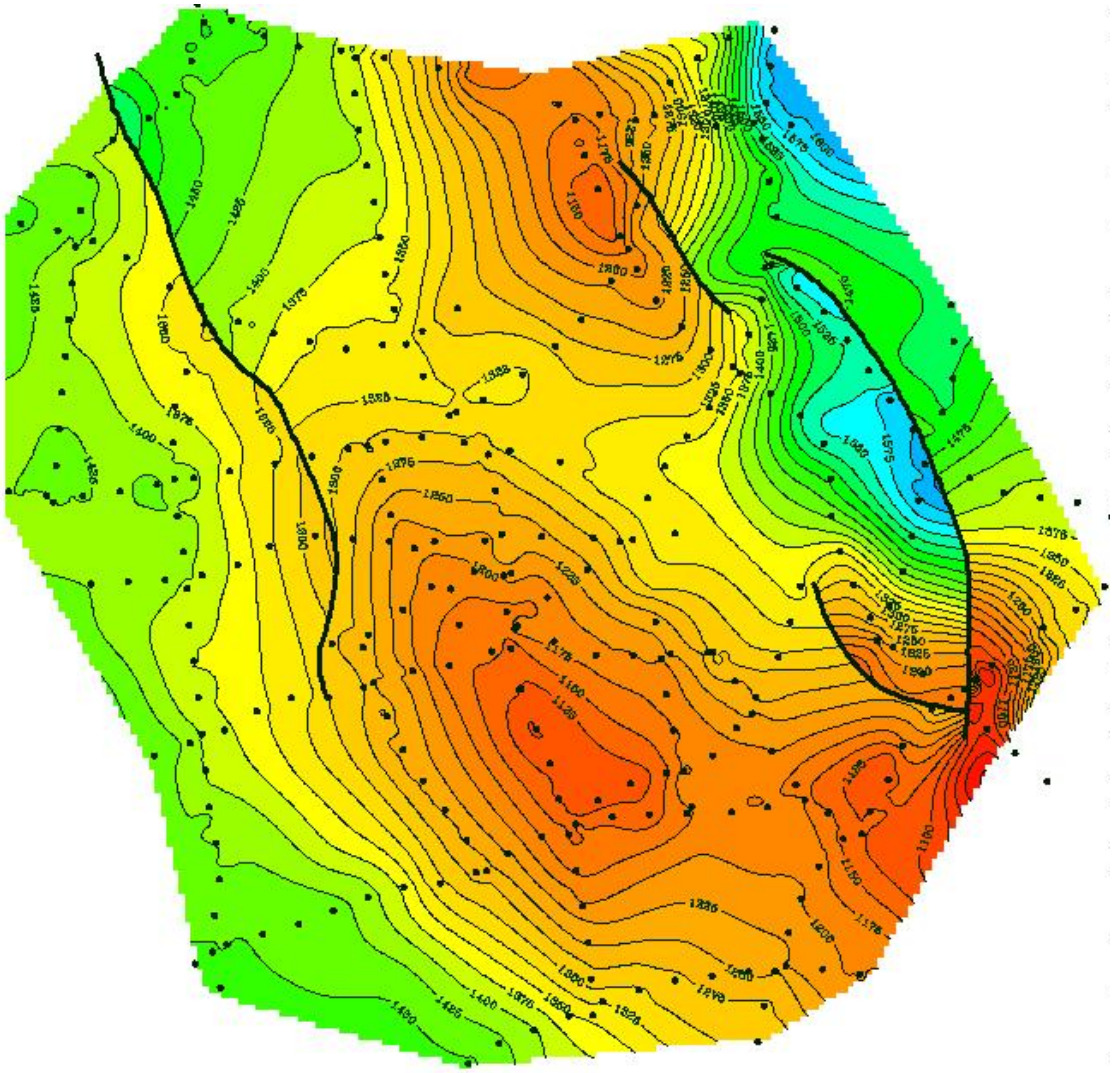

Fig. 13: Top Haldager Sand Fm depth map based on PSDM depth sections.
Contour interval: 25 m
The Vedsted structure is separated from the northern 'Pandrup structure' by a saddle at 1325 m. The mapped crest at Vedsted is at 1090 m and the spillpoint to the south-east is at 1175 m on line 08VAT08. Formation pick at Vedsted -1 is 1144m.

Base Haldager Sand Formation (MCU) depth map

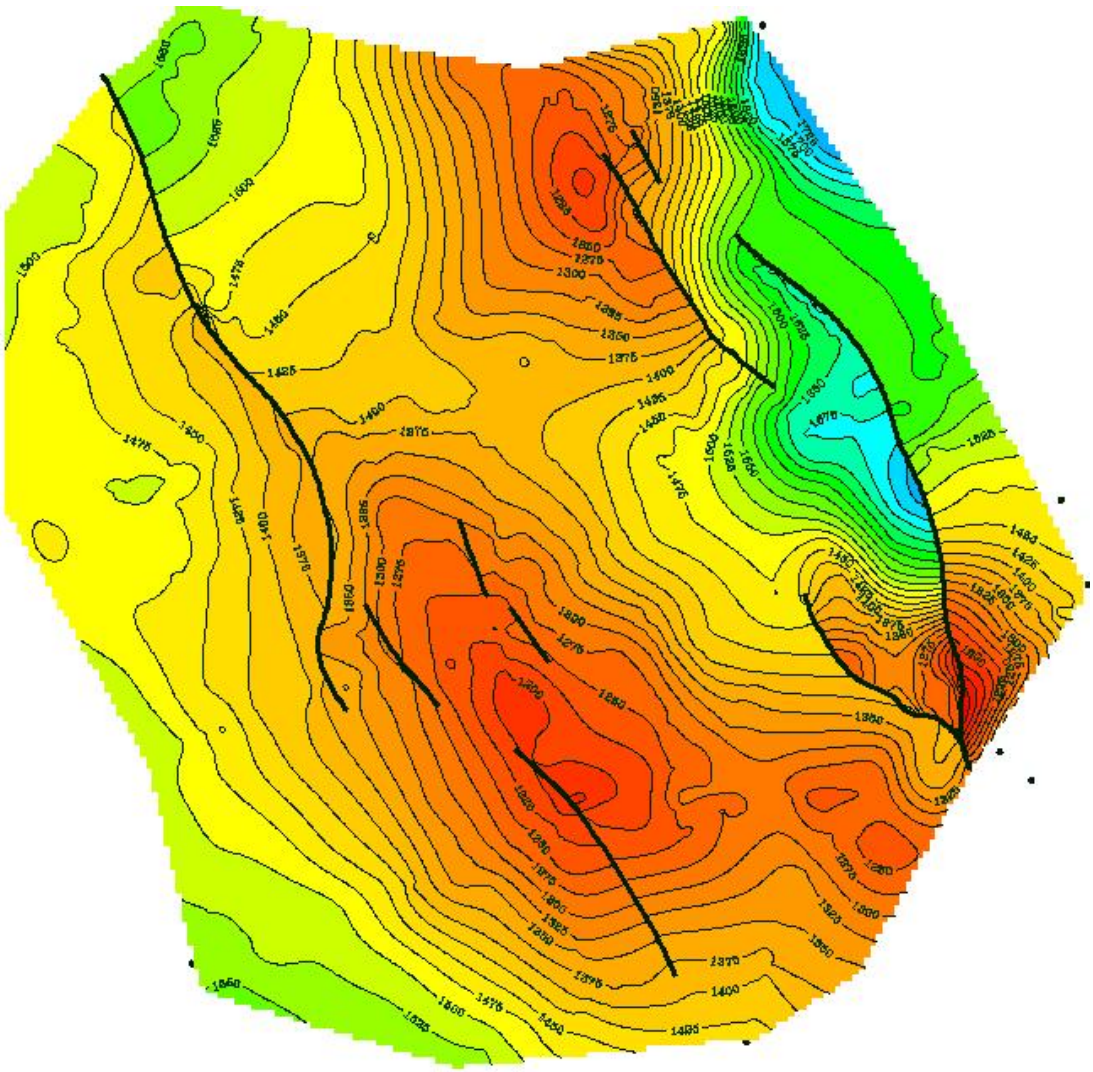

Fig.14: Base Haldager Sand Fm (MCU) depth map based on PSDM depth sections.
Contour interval: 25 m.
Note: Compared to the Top Haldager Sand Fm map a number of minor faults cut the surface in the crestal area.

Haldager Sand Formation isochore

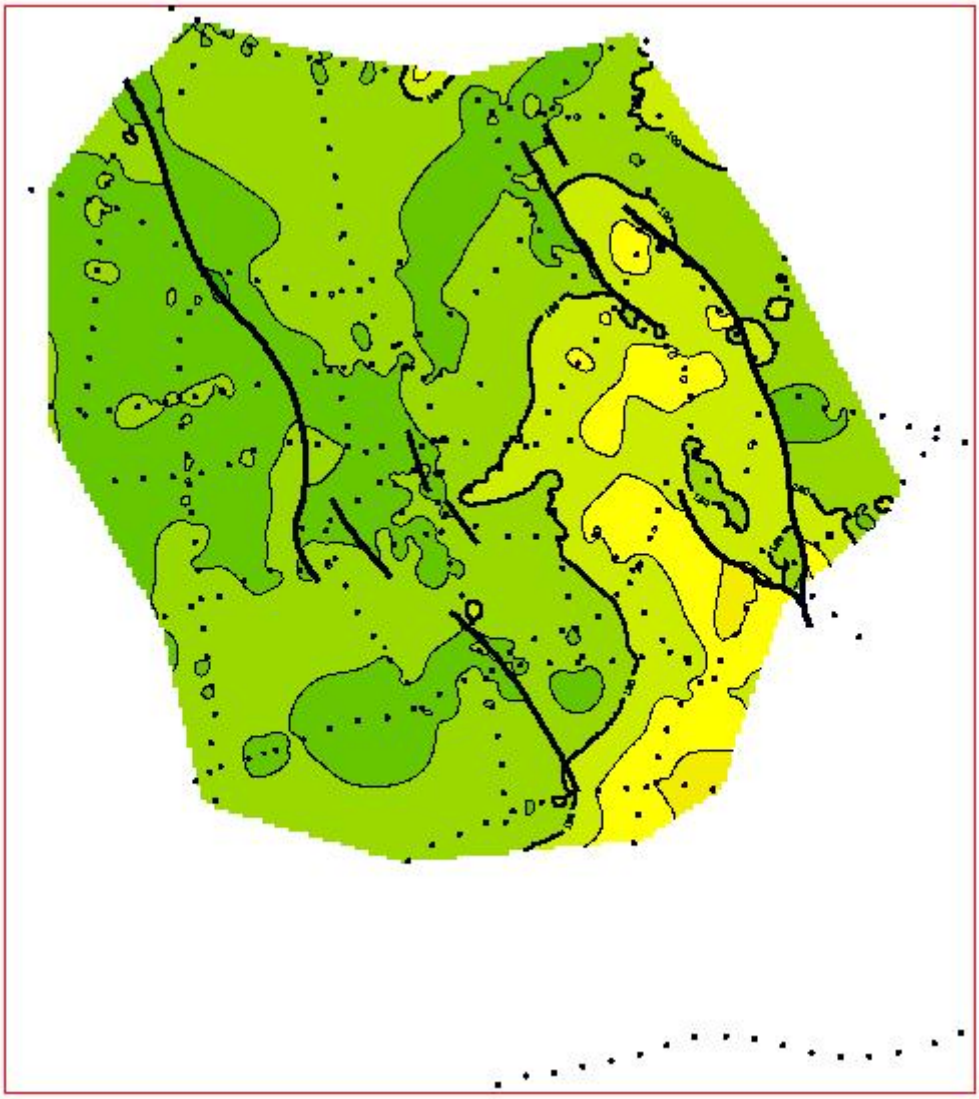

Fig. 15: Haldager Sand Fm isochore based on subtraction of Top Haldager Sand Fm from Base Haldager Sand Fm horizons in Seisworks and subsequent gridding. Contour interval: 25 m.

The mapped isochores are in agreement with drilled thicknesses increasing from 75 m in Vedsted-1 to 155 m in Haldager-1.

Near Top Gassum Formation depth map

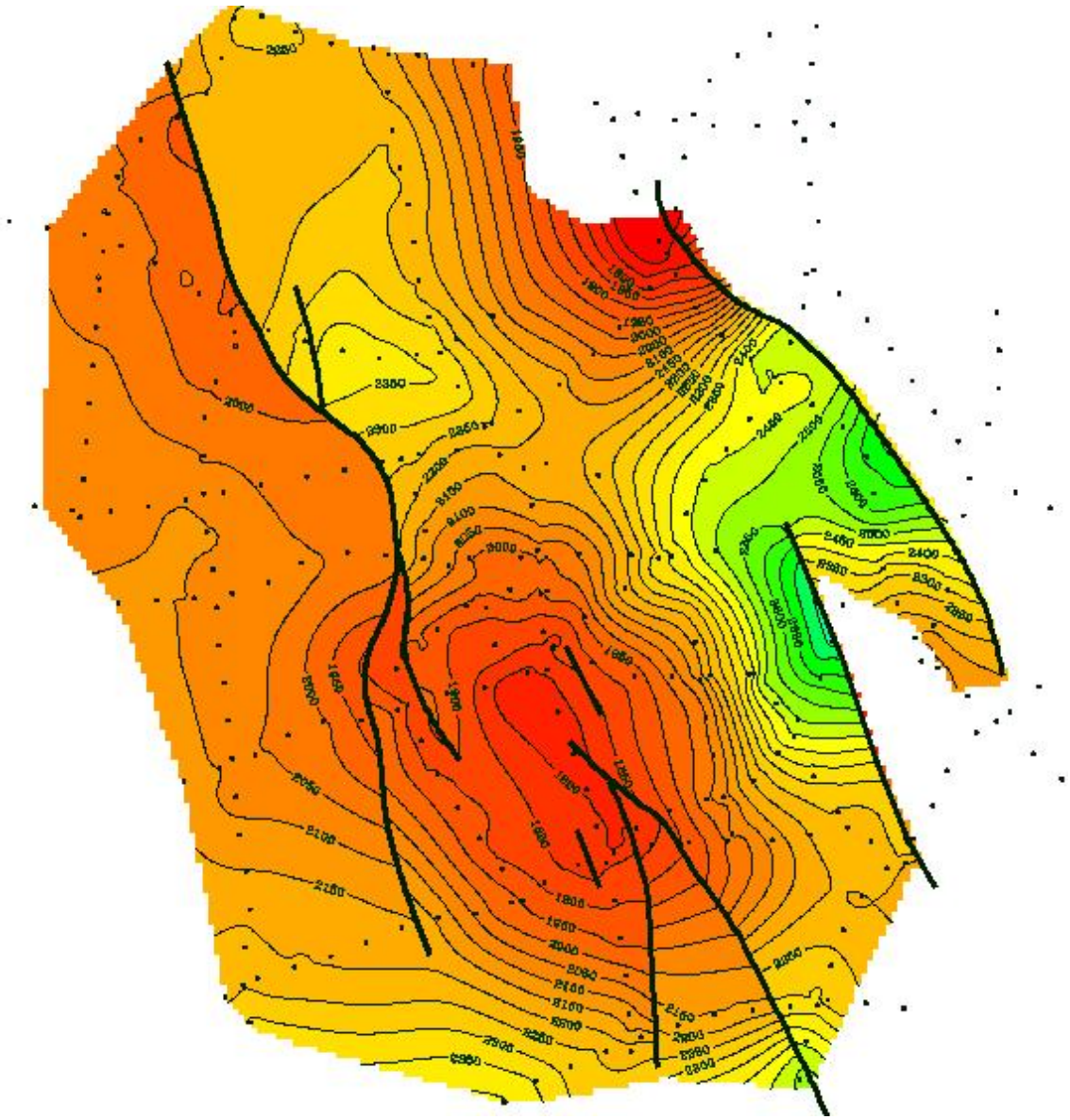

Fig. 16: Near Top Gassum Fm depth map based on PSDM depth sections.
Contour interval 50 m.
Mapped apex at 1780 m, last closing contour at 2000 west of growth fault.

Near Top Skagerrak Formation depth map

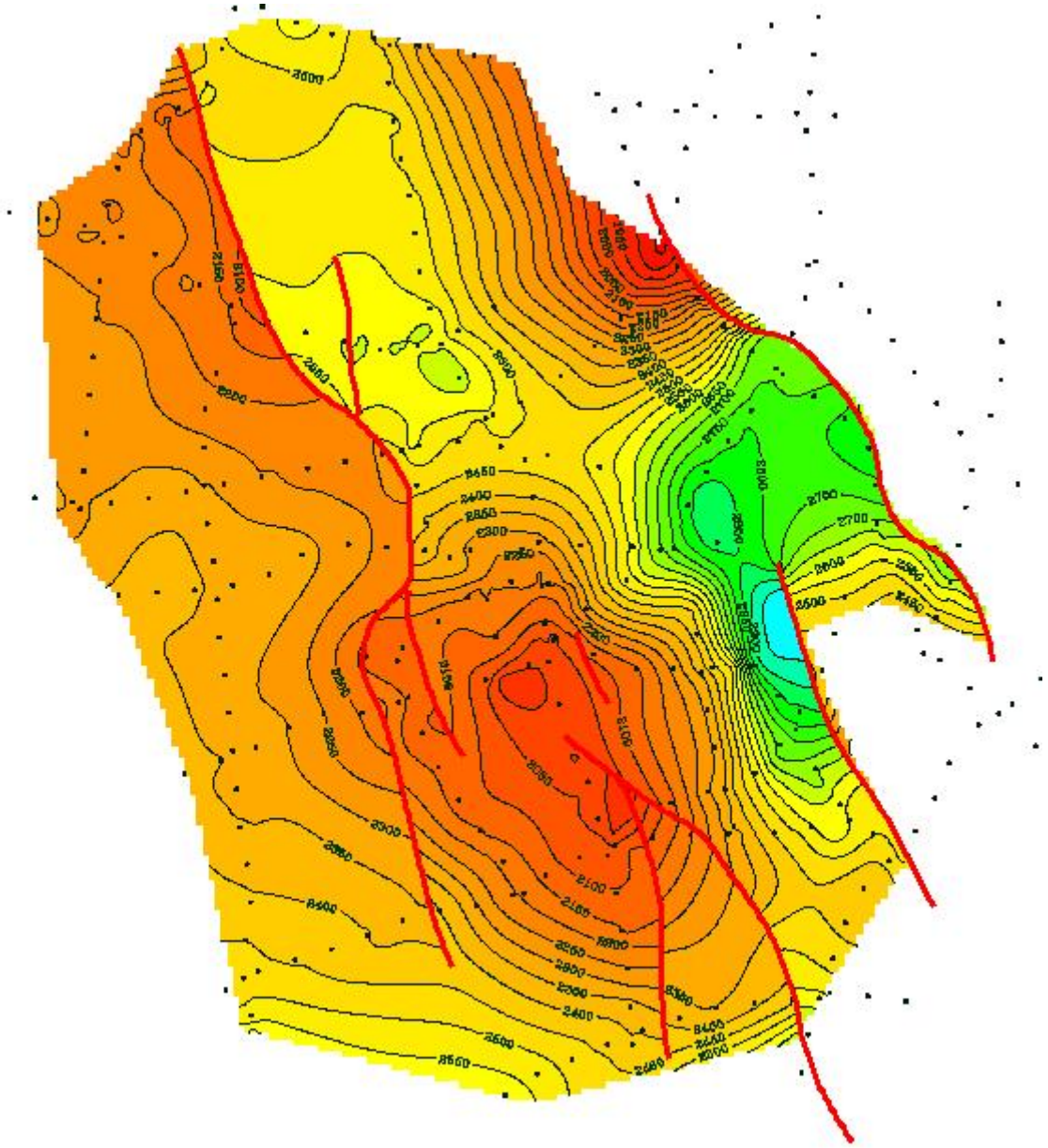

Fig. 17: Near Top Skagerrak Fm depth map based on PSDM depth sections
Contour interval 50 m.

‘Gassum’ isochore

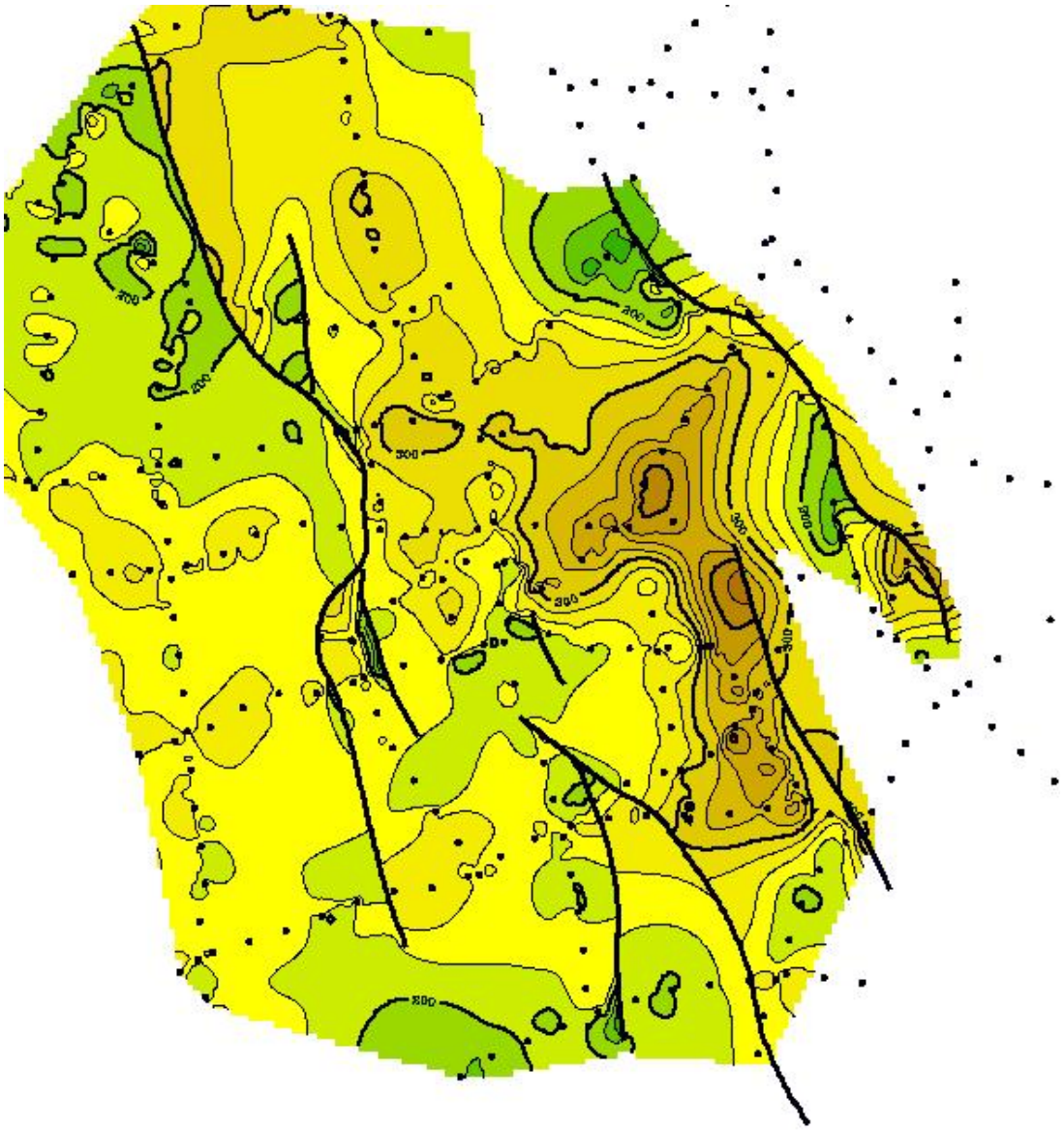

Fig. 18: ‘Gassum’ isochore with contour interval of 25 m. The map has been generated by subtraction of the Near Top Gassum Fm horizon from the Near Top Skagerrak Fm horizon in Seisworks and subsequent gridding in Z-map Plus.
Note: Artefacts caused by inclined fault planes. The ‘Gassum’ increases in thickness on the hangingwall of the growth fault in NW. The increased isochore values on the eastern flank of the Vedsted Structure are partly caused by strong structural dips.
The drilled gross thickness of the Gassum Formation including interbedded Fjerritslev Fm mudstones in Vedsted -1 is 288 m compared to the seismically mapped isochore of 225 m.

Migration velocities line 08VAT03

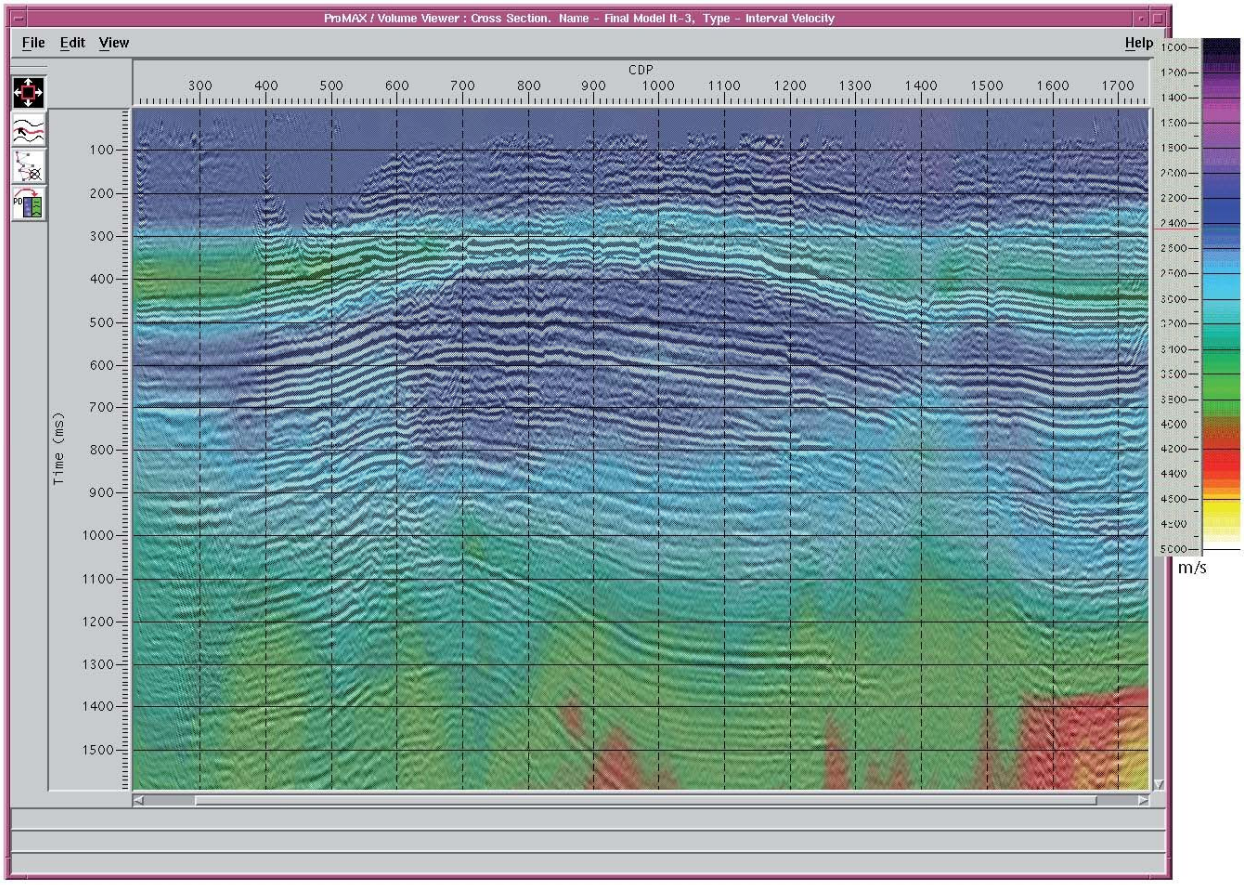

Fig. 19: Applied interval velocities on line 08VAT03 across the central part of the Vedsted Structure. Note high interval velocities (above 3000 m/sec) in the basal part of the Chalk section on the flanks at 350 to 450 ms. Below the velocity inversion at Base Chalk the interval velocities increase gradually with depth.

Average velocities from surface to Near Top Gassum Formation

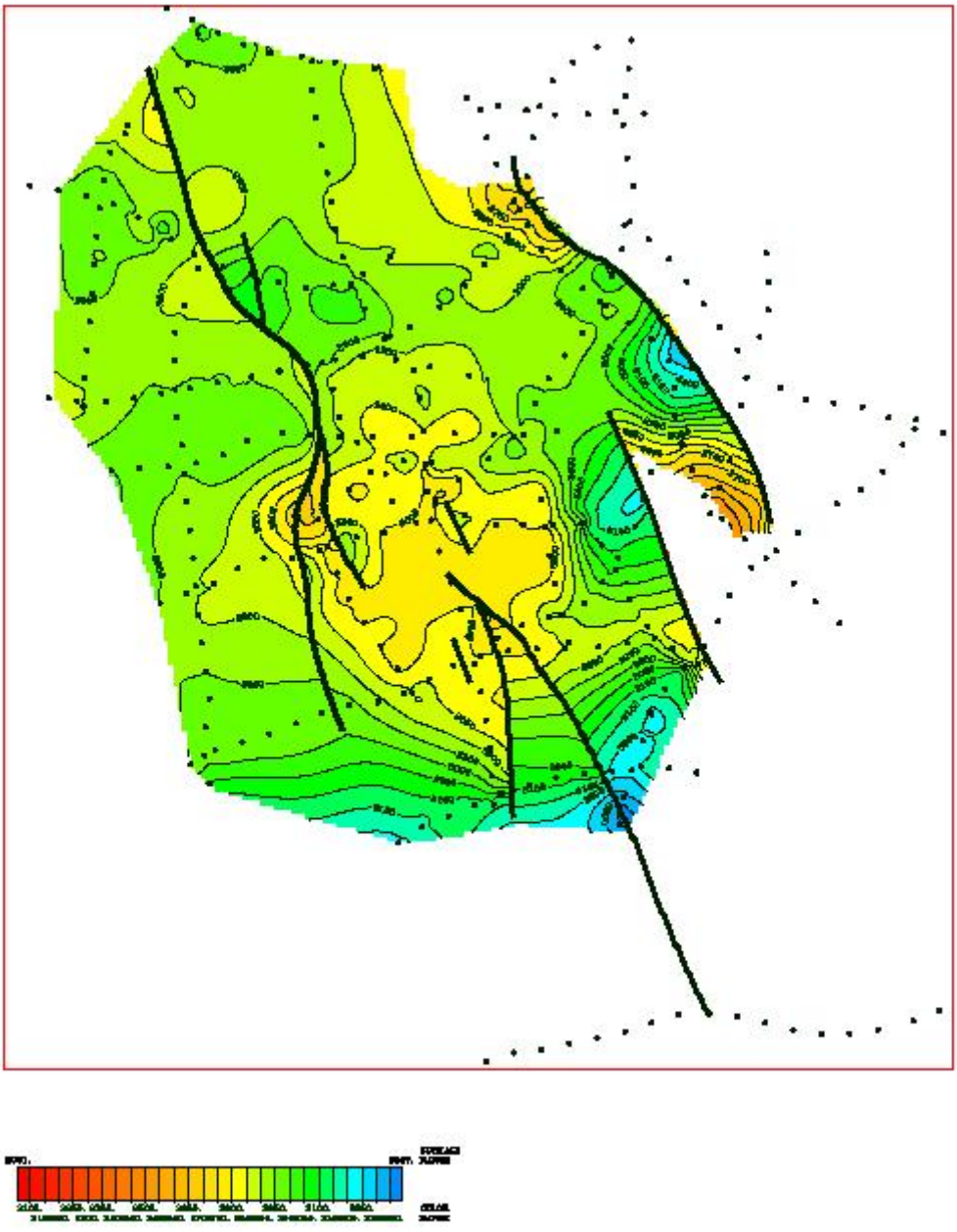

Fig. 20: Average velocities from surface to Near Top Gassum Fm generated by division of Near Top Gassum Fm depth grid by Near Top Gassum Fm time grid. Contour interval: 50 m/sec. The resulting V_{avg} is relatively uniform in the crestal part at about 2800 m/sec increasing to about 3200 m/sec on the lower flanks.