DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2012/100

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Contribution to an evaluation of the geothermal potential

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Preface

This report is prepared by GEUS for Rambøll Denmark A/S on behalf of Horsens Varmeværk a.m.b.a. with the objective to assess the geothermal potential of the Gassum Formation and the Bunter Sandstone Formation in the Horsens area.

The report builds on all available and released data that are relevant for an evaluation of the geothermal potential in the area of interest (so far the area of interest has not been fully specified by Horsens Varmeværk). The present database includes 2D seismic data, well data, wireline log data, a core from the Horsens-1 well, core analysis data, and cuttings descriptions. Data from Horsens-1 have been supplemented by log data, seismic time-depth data etc. from the Jelling-1 and Løve-1 wells located southwest of Horsens. The Horsens-1 well provides information about the Gassum Formation, but information about the Bunter Sandstone Formation is not available from Horsens-1 as the well is not deep enough.

The report includes:

1. An assessment of the potential reservoirs in the Horsens area based on well data (from the Horsens-1, Jelling-1, Løve-1, Rønde-1 and Gassum-1) and GEUS‟ regional geological model, focussing primarily on the Gassum and Bunter Sandstone formations.
2. A petrophysical evaluation of the Horsens-1, Jelling-1 and Løve-1 wells in order to assess the net sand thickness, net-to-gross ratio, reservoir porosity and permeability of the Gassum and Bunter Sandstone formations.
3. An interpretation of the existing released seismic data in the greater Horsens-Jelling area in order to map the distribution, depth and lateral continuity of the Gassum and Bunter Sandstone formations.

CONTENT

1 Dansk resumé

Det geotermiske potentiale omkring Horsens by er blevet evalueret på baggrund af seismiske data samt datamateriale indsamlet i forbindelse med udførelsen de tre dybe efterforskningsboringer Horsens-1, Jelling-1 og Løve-1. Rapporten fokuserer på en analyse af det geotermiske potentiale i henholdsvis Gassum Formationen og Bunter Sandsten Formationen.

Opbygningen af den geologiske lagserie i boringerne Horsens-1, Jelling-1 og Løve-1 er undersøgt ud fra en analyse af borespåner, kernemateriale og petrofysiske borehulsmålinger (logs). Desuden er de geologiske forhold vurderet med udgangspunkt i GEUS‟ regionale geologiske model for området, og herudover der er indhentet informationer fra forskellige boringsrapporter, herunder "Well Completion Reports". Horsens-1 boringen gennemborer Gassum Formationen, men ikke Bunter Sandsten Formationen, og vurderingen af potentialet i Bunter Sandsten Formationen er derfor baseret på data fra Jelling-1 og Løve-1 boringerne, som er de nærmeste dybe boringer.

GEUS har udført en petrofysisk evaluering af de borehulsmålinger (logs), der er optaget i boringerne umiddelbart efter at borearbejdet blev afsluttet. Formålet med denne analyse er at bestemme reservoir-egenskaberne for de sandstenlag, der er relevante for geotermisk produktion. I Horsens-1 boringen er Gassum Formationen 94 meter tyk, men kun omtrent en tredjedel kan betegnes som egentligt reservoirsandsten, og ud fra logtolkningen er reservoir-sandstenens tykkelse vurderet til ca. 28 meter med en tilhørende porøsitet på ca. 25%. Med hensyn til Bunter Sandsten Formationen i Jelling-1 og Løve-1 boringerne er der tolket reservoirsandstens-tykkelser på henholdsvis 50 og 150 meter, og de tilhørende porøsiteter er ca. 20–25%. Selv om permeabiliteten er en væsentlig reservoirparameter, eksisterer der ikke en egentlig permeabilitets-log, og derfor må permeabiliteten vurderes via en indirekte metode. Som følge af denne tekniske begrænsning har GEUS estimeret permeabiliteten ud fra en antaget sammenhæng mellem porøsitet og permeabilitet.

Der er i dag kun en begrænset mængde seismiske data (linier) til rådighed indenfor Horsens området, og en del af disse er af ringe kvalitet. Dog er de nyeste seismiske data indsamlet i Jelling-Løve området af virkelig god kvalitet. I forbindelse med denne indledende evaluering af det geotermiske potentiale er stort set alle til rådighed værende seismiske data tolket indenfor et større område, der bl.a. indbefatter Horsens-1, Jelling-1 og Løve-1 boringerne. Resultatet af den seismiske tolkning er først og fremmest en vurdering af Gassum og Bunter reservoirernes udbredelse og dybdeforhold. De mange forkastninger, der er i området, komplicerer den seismiske tolkning, og derfor er der indtil videre kun fremstillet overordnede dybdekort med markering af de mest fremtrædende forkastninger. På baggrund af den ringe data-dækning og de mange forkastninger indenfor området anbefaler GEUS, at næste skridt i modningen af det geotermiske prospekt bliver indsamling af nye seismiske data.

På baggrund af de petrofysiske og seismiske tolkninger vurderer GEUS, at Gassum Formationen har et geotermiske potentiale ved Horsens-1 boringen og antagelig også i et område omkring Horsens by, idet Horsens-1 boringen anses for repræsentativ for de geologiske forhold indenfor et større område omkring boringen, forudsat at lagfølgen ikke forstyrres af markante forkastninger.

Ligeledes vurderer GEUS, at Bunter Sandsten Formationen har et geotermiske potentiale ved Jelling-1 og Løve-1 boringerne. GEUS‟ regionale geologiske model samt de undersøgelser, som GEUS har udført, peger på, at reservoirforholdene ved de to boringer også kan være gældende for et område omkring Horsens by, således at Bunter Sandsten Formationen sandsynligvis har et geotermisk potentiale i området ved Horsens by. Da både Jelling-1 og Løve-1 ligger et godt stykke fra Horsens, er GEUS‟ vurdering af Bunter Sandsten Formationens potentiale ved Horsens by dog behæftet med relativ stor usikkerhed.

2 Introduction

The general guidelines for suitable geothermal reservoirs in the subsurface fulfilling the requirements for safe, sustainable and economic exploitation of geothermal water are based on the experiences that GEUS in collaboration with DONG Energy previously have established. As a rule of thumb the reservoir interval needs to be reasonably thick, situated at a depth of 800–3000 m and preferably dominated by medium-grained or coarser-grained sandstones. The lower depth limit is selected due to the increasing risk of insufficient porosity and permeability in reservoirs at depths exceeding 3000 m. The upper limit is selected to ensure that formation water has a sufficient temperature. Usually, the temperature of reservoirs shallower than *c.* 800 meters (i.e. 20–30ºC) is too cold for geothermal production.

This report presents the preliminary results of an evaluation of the reservoir quality of the potential geothermal reservoirs in the Horsens area, i.e. the Upper Triassic–Lower Jurassic Gassum Formation and the Lower Triassic Bunter Sandstone Formation. The study is building on GEUS’ regional geological models and based on a local dataset comprising seismic data, wireline logs, cores etc. supplemented with descriptions of cuttings and side wall cores, refer to the Horsens-1, Jelling-1 and Løve-1 Well Completion Reports. The study is carried out for Rambøll Danmark A/S on behalf of Horsens Varmeværk a.m.b.a.

The well data used for evaluating the geothermal potential arise primarily from Horsens-1 drilled in 1958, Jelling-1 (1992) and Løve-1 (2011), but well data from Rønde-1 and Gassum-1 are also included. Information on the geology of the drilled sections and the lithostratigraphic subdivision is available from Wells Completion reports and tables presented in Nielsen & Japsen (1991). The seismic interpretation is based on available 2D seismic lines that have been tied to well-known lithostratigraphic tops (or picks) at well locations. The existing 2D seismic lines are of various quality and vintage (Fig. 1), and it is noteworthy that only one line intersects the Horsens-1 well location (Fig. 2).

3 Geological background

The Horsens area is located in the Danish part of the Norwegian–Danish Basin. The basin was formed by crustal stretching followed by late Carboniferous-Early Permian rifting and Mesozoic–Cenozoic thermal-dominated subsidence. As a result a succession of several kilometers of evaporites, sandstones, siltstones, mudstones and carbonates accumulated in the basin. This succession contains several potential geothermal sandstone reservoirs of which the Gassum Formation and the Bunter Sandstone Formation constitute the principal reservoirs (Mathiesen et al. 2009).

3.1 Gassum Formation

The Upper Triassic–Lower Jurassic Gassum Formation has been penetrated by many wells proving that the formation is present in most of the Norwegian-Danish Basin except for significant salt structures and on the high-lying basement blocks of the Ringkøbing-Fyn High (Michelsen et al. 2003; Nielsen 2003). The formation consists mainly of marine and fluvial sandstones interbedded with marine and lagoonal mudstones, minor siltstones and thin coal beds formed during a period with recurrent sea-level changes. Generally the sandstones are considered to be widespread with relatively good lateral continuity in areas unaffected by faults or salt structures.

3.2 Bunter Sandstone Formation

The Lower Triassic Bunter Sandstone Formation occurs widespread in the Norwegian-Danish Basin and the North German Basin as shown by several deep wells. The formation accumulated during a period dominated by an arid climate. The sandstones were mainly deposited by ephemeral braided rivers and windblown dunes. Interbedded mudstones and siltstones, occasionally with evaporates, were mainly formed in shallow, ephemeral lakes and sabkhas. Generally, the sandstones are considered to be widespread with relatively good lateral continuity in areas unaffected by faults or salt structures.

4 Assessment of the reservoir quality in the Horsens area

The evaluation of reservoir quality of the Gassum Sandstone Formation is based primarily on wireline logs and core analysis data from the Horsens-1 well. The Horsens-1 well is not deep enough for penetrating the Bunter Sandstone Formation, but the seismic data indicate that the Bunter Sandstone Formation is present at a deeper level. Consequently, the evaluation of the reservoir quality of the Bunter Sandstone Formation at Horsens must be based on log data etc. that have been acquired in wells located outside the Horsens area. In this context GEUS´s general knowledge of the regional geology combined with information on the depositional environment is utilised.

4.1 Database, log quality and petrophysical evaluation

The petrophysical evaluation is based on the wireline logs acquired in the three wells (listed in Table 1**)** along with relevant information extracted from well completion reports etc. A full log suite is available from Jelling-1 and Løve-1, but the Horsens-1 log set is old and incomplete which complicates a reliable porosity determination. In general, the quality of the logs actually acquired is good.

Table 1: List of raw logs and interpreted log curves for the Horsens-1, Jelling-1 and Løve-1 wells

Log name	Description, application and comments
GR	Gamma-ray log (API). Measuring natural radioactivity
SP	Spontaneous Potential (milli Volt); measuring electric potential. ***A SP log was recorded in Horsens-1.*** A re-scaled SP log in herein termed GRpseudo.
CALI / HCAL	Caliper log (inches). Measuring borehole size (diameter)
DT	Sonic log (micro-sec/ft). Acoustic log measuring travel time (/velocity)
RHOB /RHOZ	Density log (g/cc). Measuring bulk density
NPHI	Neutron porosity (fraction). Measuring apparent porosity
RD	Deep reading log (ohmm). Measuring resistivity
RS	Shallow reading log (ohmm). Measuring resistivity
RT_HLRT	„True" resistivity (ohmm); measuring resistivity
18F8	Old resistivity log (ohmm); laterolog, spacing 18ft 8 inch. ***Recorded in Horsens-1***
64IN	Old normal resistivity log (ohmm); spacing 64 inch. ***Recorded in Horsens-1***
PHIT	Log-derived *total* porosity (fraction). Interpreted/calculated log curve
PHIE	Log-derived *effective* porosity (fraction). Interpreted/calculated log curve
PERM_log	Log-derived permeability (mD). Interpreted/calculated log curve
Vshale	Log-derived shale volume (fraction). Interpreted/calculated log curve

4.2 Interpretation of lithology

The lithologies of the drilled well sections are interpreted using raw log data, description of cuttings, cores and sidewall cores along with information from well completion reports and mud logs. A lithology column, bounded by a modified SP log in Horsens-1 – and the gamma-ray and sonic logs in the Jelling-1 and Løve-1 wells – is generated for each well (refer to Figs 4–6).

According to the cuttings descriptions available from the Horsens-1 Well Completion Report, the sandstone layers of the Gassum Formation consist of **fine to medium-grained sandstone**, but the individual sandstone layers are not characterised as either fine-grained or medium-grained (i.e. only the overall grain size distribution is available from the cuttings descriptions). Neutron and density logs were not acquired in the Horsens-1 wells, meaning that it is not possible to differentiate between fine-grained and medium-grained sandstone layers on the basis of log responses.

In Jelling-1, the Bunter Sandstone Formation consists primarily of fine-grained sandstones. The sandstone layers are mostly made up of loose grains and occasionally, the Bunter Sandstone is calcite cemented. The sandstone interval (1655-1750m MD) is interbedded with minor siltstone and claystone layers at certain levels.

In Løve-1, the Bunter Sandstone Formation is dominated by sandstones with minor claystone interbeds. The sandy part of the formation consists largely of fine to medium-grained sandstones. The sandstones are well sorted and consist predominantly of quartz grains that are loosely cemented. Occasionally the sandstones are calcite cemented, however.

To some extent the Jelling-1 and Løve-1 well sections are differently developed with respect to the dominating grain size of the Bunter sandstones as described above. This difference is reflected in the log responses, as the separation between the neutron and density logs differs slightly in the two wells (refer to the NPHI-RHOB and NPHI-RHOZ curves plotted in Figs 4–5). It appears from the figures that the „sandstone separation" is more pronounced in Løve-1 than in Jelling-1, and the „sandstone separation" is partly suppressed in Jelling-1 due the presence of fine-grained material.

4.3 Evaluation of shale volume and porosity

Normally the shale volume is calculated from the gamma-ray (GR) log using well-specific shale parameters, i.e. background radiation (GR_min) and the GR response for the clay-rich matrix (GR_max); refer to Table 2. The shale volume (Vshale) is calculated as follows:

$$\text{Vshale} = (\text{GR} - \text{GR\_min})/(\text{GR\_max} - \text{GR\_min})$$

No GR log is, however, available from the Horsens-1 well and instead the shale volume is calculated from the SP log using a similar methodology.

Table 2: Parameters used for interpreting the shale volume from the gamma-ray (GR) and SP logs

Well	**Zone/ Formation**	**Interval (m MD)**	**GR_min (API) SP_min (mV)**	**GR_max (API) SP_max (mV)**
Horsens-1	Gassum	1506-1600	74	166
Jelling-1	Bunter Sst.	1635-1750	35	150
Løve-1	Bunter Sst.	1822-2059	50	160

Subsequent to the calculation of the shale volume, the porosity in Jelling-1 and Løve-1 was determined from a shale-corrected density log using a standard petrophysical approach. A porosity log was not acquired in Horsens-1 and consequently, the porosity evaluation is based on the *resistivity* log (64 inch) combined with core porosity data; the core data (point data) are used for calibrating and adjusting the log-derived porosity. Further details on the porosity determination using the resistivity log and the shale volume are outlined below.

The Archie Equation relates the water saturation (*Sw*) to the *resistivity* log and the total porosity (*PHIT*):

$(Sw)^2 = \dfrac{a \cdot Rw}{resistivity \cdot (PHIT)^2}$, where *a* and *Rw* are petrophysical constants.

So for Sw = 1 and $a{\cdot}Rw$ = 0.040 *ohmm*, the porosity is given by $PHIT = \sqrt{0.04 ohmm / restistivity}$

Next the effective porosity (PHIE) can be calculated as follows: PHIE = *PHIT–PHIT*·Vshale.

4.4 Permeability

A reliable permeability log does not exist, but a reasonable permeability estimate can be derived from a porosity-permeability relationship set up on the basis of core data. GEUS has established such a porosity-permeability relation using a regional dataset, which encompasses data from several Danish onshore wells (Fig. 3; note that the core permeability data are gas/air permeabilities). A short conventional core was cut in a part of the Gassum

Formation in the Horsens-1 well and the core analysis data are listed below. Conventional cores were not cut in Jelling-1 or in Løve-1. The regional model estimates the permeability (PERM_log) on the basis of the log porosity (PHIE) using a power function:

$$\text{PERM\_log} = 196449 \cdot (\text{PHIE})^{4.3762}$$

where PHIE is expressed as a fraction and the log-derived gas permeability (PERM_log) is expressed in millidarcies (mD). The regional model includes data from Haldager Sand, Gassum and Bunter Sandstone formations, aiming at establishing a greater database. It is assumed that the regional GEUS model can be used to estimate an *average* permeability value of the Gassum and Bunter reservoir sandstones, despite that it is not possible to calibrate the regional model against a local dataset that includes core analysis data from either Jelling-1 or Løve-1. The limited core data from the Gassum Formation in Horsens-1 reasonably fit into the regional model. The lack of local permeability measurements from the Bunter Sandstone Formation in Jelling-1 and Løve-1 adds to the uncertainty on the permeability estimates in these two wells (see also section 4.5). The geological description of the Gassum Formation in the Horsens-1 well indicates that the grain size of the sandstone layers varies, but it is not possible to differentiate between fine-grained and medium-grained intervals due poor logs and very brief cuttings descriptions. On this basis it was decided to use the regional GEUS model for estimating the permeabilities in the Gassum Formation. The lithology of the Bunter Sandstone Formation in Jelling-1 and Løve-1 is described in section 4.2, and since the cuttings descriptions from these wells point to two different grain size distributions, the overall regional GEUS model was used for assessing permeabilities also in the Bunter Sandstone Formation. The regional model is considered more generally applicable, and to some extent it takes grain size variations into account.

Table 3: Core analysis data from a minor interval of the Gassum Formation in the Horsens-1 well

Plug	Core No.	Depth (m MD)	Plug orientation	Gas perm (mD)	Porosity (%)	Lithological Comments
1	4	1583.45	H	999	37.6	Fine-grained sandstone and Medium-grained sandstone
2	4	1583.75	H	1178	34.4	
3	4	1584.70	H	15	22.7	
4	4	1584.90	H	160	26.2	
5	4	1585.75	H	3484	30.0	
6	4	1585.90	V	2	5.0	
7	4	1586.20	H	5	5.4	

4.5 Results of petrophysical evaluation and reservoir parameters

The result of the petrophysical evaluation is presented in plots (Figs 4–6) and tables of reservoir parameters (Table 5a–d). The tabulation encompasses: formation thickness, accumulated net sand thickness, net-to-gross ratio and average net porosity along with estimated permeability. Prior to calculating reservoir parameters, cut-offs were applied to examine the sensitivity to variations in porosity (PHIE) and shale content (Vshale).

A 30% Vshale cut-off was applied to exclude claystones and shaly sandstones with a poor reservoir potential. Furthermore, various porosity cut-offs were applied to qualify and characterise the potential reservoir sandstones. This analysis results in an assessment of the accumulated net sand thickness based on a certain minimum porosity**.** Four sets of minimum porosities have been considered: 0%, 10%, 15% and 20% as listed in Table 5a–d (the 0% scenario corresponds to no porosity cut-off). The net-to-gross ratio, which is abbreviated N/G in the tables, is calculated for each interval separately, and N/G equals „net sand thickness" divided by „interval thickness".

The permeability (right column in Table 5) is not a direct measurement, but it is estimated from a porosity-permeability relationship that has been derived from core analysis data as described above (Fig. 3).

The quality of the logs acquired in Jelling-1 and Løve-1 is very good and the uncertainty on the porosity determination is presumably close to ±2 porosity units (±2% absolute). The lack of a directly recorded porosity log in Horsens-1 means that the uncertainty on the porosity evaluation is higher in this well, possibly ±4 porosity units. The absence of direct permeability measurements, apart from a few core permeability data are available from Horsens-1, leads to considerable uncertainty on the permeability estimates listed in Table 5. Hence GEUS suggest to associate the most likely permeability values with an uncertainty band (High–Low range) defined on the basis of the general trend line presented in Fig. 3, i.e. High case: general trend times 5; Low case: general trend divided by 5.

The petrophysical evaluation, supplemented with transmissibility assessments, indicates that the **Gassum Formation** has a geothermal potential in the Horsens-1 well. An approximately 28m thick reservoir interval with an average porosity greater than 25% is interpreted from the log data. The lack of a directly recorded porosity log in Horsens-1 introduces, however, uncertainty on the porosity evaluation outside the cored interval (1583–1587m MD).

Furthermore, the log analysis indicates that the **Bunter Sandstone Formation** has a geothermal potential both in Jelling-1 and Løve-1, although the formation is significantly thicker in Løve-1 than in Jelling-1. The net sand thickness is about 80m in Jelling-1, but 150–200m in Løve-1 depending on the applied cut-off values. The average reservoir porosity is reasonably high in both wells, i.e. *c*. 21% in Jelling-1 and *c*. 23% in Løve-1 (provided that a 15% porosity cut-off is applied).

The estimated permeabilities for both formations are associated with uncertainty, and so are the assessed transmissibilities, i.e. permeability times net sand thickness. Preliminary transmissibilities have been calculated for the reservoir sections and these estimates point toward good reservoir properties, refer to Table 4 below:

Table 4: Estimated transmissibilities

Well	**Formation**	**Depth (metres MD)**	**Gas Transmissibility (Darcy-meter)**
Horsens-1	Gassum	1506-1600	15
Jelling-1	Bunter Sandstone	1635-1750	16
Løve-1	Bunter Sandstone	1822-2059	60

The **Bunter Sandstone Formation** is not drilled in the Horsens-1 well, but the seismic data indicate that the formation is present in the area, i.e. at a deeper level than the total depth of the Horsens-1 well. The assumed depth of the Bunter Sandstone Formation at Horsens-1 is approx. 2000 metres that is somewhat deeper than observed in the Jelling-1 and Løve-1 wells (refer to Chapter 5). The greater depth at Horsens most likely has resulted in slightly lower reservoir porosities and permeabilities than interpreted from the log data in the Jelling-1 and Løve-1 wells.

According to Bertelsen (1980), the Bunter sandstones occurring in the Norwegian–Danish Basin were mainly derived from the north and northeast (i.e. Fennoscandia). The Horsens area is located somewhat closer to the assumed sediment source area than Jelling, suggesting that the gross sand content of the Bunter Sandstone Formation may be higher at Horsens compared to the Jelling area. However, a complementary study of the geological evolution in early Triassic time along with further investigations of the potential sediment source areas are needed to confirm or disprove this assumption. The Rønde-1 and Gassum-1 wells located north of the Horsens area (Fig. 1) are both characterised by a thick and very sandy Bunter Sandstone Formation, and this sand distribution is in agreement with the depositional model described by Bertelsen (1980). The high sand content of the Bunter Sandstone Formation in the Rønde-1, Gassum-1, Jelling-1 and Løve-1 wells is thus considered positive for the sandstone distribution to be expected in the „Bunter reservoir" at Horsens. For a further and more detailed assessment of the „Bunter reservoir" at Horsens, GEUS recommend to conduct a more comprehensive regional geological study, including e.g. detailed correlation of wireline logs from several key wells as well as an analysis of petrographic data from cores of the Bunter Sandstone Formation. Such a study should also examine and analyse the lateral continuity of the sandstone layers present in the Bunter Sandstone Formation. As the Bunter Sandstone Formation in the Horsens area may be affected by diagenesis in certain intervals, the study should address the potential effects of possible diagenetic processes such as those described by e.g. Weibel (1998 and 1999) and Weibel & Friis (2004). It is expected that the study will make it possible to better constrain and extrapolate reservoir properties (e.g. porosities, thicknesses, clay content etc.) into the Horsens area with greater confidence.

The Horsens-1 well demonstrated the presence of a **Gassum Formation reservoir**, but the Gassum Formation is not present in Løve-1 nor in Jelling-1; i.e. the Gassum Formation is missing in an area toward the Ringkøbing–Fyn High due to post-depositional truncation (refer to Chapter 5 and Enclosure 1).

Table 5a:
Wells: Horsens, Jelling-1 and Løve-1
Analysis of reservoir sands
Reservoir parameters for net (gross) sand
Net sand defined as sandstone with < 30% shale, and porosity > 0%

Well	Interval name	Interval (m MD)	Gross thickness (m)	Net sand thickness (m)	N/G	Average porosity (%)	Estimated gas Perm. (mD)
Horsens-1	**Gassum**	1506–1600	94	28*	0.30	26.0	540
Jelling-1	**Bunter**	1635–1750	115	104*	0.90	17.7	85
Løve-1	**Bunter**	1822–2059	237	213*	0.90	21.8	250

*Accumulated

Table 5b:
Wells: Horsens, Jelling-1 and Løve-1
Analysis of reservoir sands
Reservoir parameters for net sand
Net sand defined as sandstone with < 30% shale, and porosity > 10%

Well	Interval name	Interval (m MD)	Gross thickness (m)	Net sand thickness (m)	N/G	Average porosity (%)	Estimated gas Perm. (mD)
Horsens-1	**Gassum**	1506–1600	94	28*	0.30	26.0	540
Jelling-1	**Bunter**	1635–1750	115	91*	0.79	19.8	165
Løve-1	**Bunter**	1822–2059	237	208*	0.88	22.2	270

*Accumulated

Table 5c:
Wells: Horsens, Jelling-1 and Løve-1
Analysis of reservoir sands
Reservoir parameters for net sand
Net sand defined as sandstone with < 30% shale, and porosity > 15%

Well	Interval name	Interval (m MD)	Gross thickness (m)	Net sand thickness (m)	N/G	Average porosity (%)	Estimated gas Perm. (mD)
Horsens-1	**Gassum**	1506–1600	94	28*	0.30	26.0	540
Jelling-1	**Bunter**	1635–1750	115	78*	0.68	21.0	210
Løve-1	**Bunter**	1822–2059	237	190*	0.80	23.0	315

*Accumulated

Table 5d:
Wells: Horsens, Jelling-1 and Løve-1
Analysis of reservoir sands
Reservoir parameters for net sand
Net sand defined as sandstone with < 30% shale, and porosity > 20%

Well	Interval name	Interval (m MD)	Gross thickness (m)	Net sand thickness (m)	N/G	Average porosity (%)	Estimated gas Perm. (mD)
Horsens-1	**Gassum**	1506–1600	94	26*	0.28	26.8	620
Jelling-1	**Bunter**	1635–1750	115	48*	0.42	23.0	315
Løve-1	**Bunter**	1822–2059	237	152*	0.64	24.4	410

*Accumulated

5 The distribution and lateral continuity of the potential reservoirs

The seismic data available around and near the Horsens area is very limited (see Figs 1 and 2). The seismic data have been interpreted in order to evaluate the distribution and lateral continuity of the potential reservoirs. The results of the seismic interpretation are illustrated by selected and relevant seismic sections displaying the geological conditions in the Jelling-Løve-Horsens area (Figs 8–10). The seismic sections show the presence of formations containing reservoirs, changes in formation thicknesses and the occurrence of significant faults.

Several of the seismic data were acquired from the mid-sixties to the mid-eighties, and have been scanned and digitised from the original paper format. Afterward the scanned and digitized lines were loaded onto a seismic workstation and incorporated in the digital database at GEUS. This procedure insures that the new interpretation can be integrated with earlier mapping efforts. This integration of all existing interpretations has resulted in maps that are more consistent on a local scale compared to the more regional maps previously published by GEUS. The new maps prepared for this study are therefore more accurate than the regional maps, and the new maps are thus considered suitable for an evaluation of seismic continuity and the depth to the reservoirs within the study area.

5.1 Seismic interpretation and mapping (TWT maps)

Nine horizons are interpreted:

- Top Chalk
- Base Upper Cretaceous (i.e. Base Chalk)
- MCU (Mid Cimmerian Unconformity)
- Near Top Gassum Fm
- Near Base Gassum Fm in parts of the study area
- Near Top Bunter Sst Fm
- Near Base Bunter Sst Fm
- Near Top Zechstein
- Near Base Zechstein/Top Pre Zechstein

The identification and definition of these horizons is based on an integration of the stratigraphic well picks with seismic reflections as interpreted form the seismic data. The subsequent seismic mapping comprises two horizons: Near Top Gassum Fm and Near Top Bunter Sst Fm (see also Enclosure 1 and 2).

The quality of the seismic data varies from line to line, and the data quality is e.g. related to the fact that the seismic lines are of different vintages. An assessment of the quality of selected seismic lines is given below:

Line No. (see also Fig. 2)	**Quality assessment**
V2 (at Horsens-1)	Poor
V12 (NW of Horsens-1)	Poor
DNJ-16 (W of Horsens-1)	Good
DNJ-26 (W of Horsens)	Good
V4 (NW of Horsens-1)	Poor
V1 (S of Horsens)	Poor
DN90D-02 (at Jelling-1 and Løve-1)	Good
80-122 (SE of Horsens)	Moderate
DN91D-04 (at Jelling-1)	Very good
DN91D-06 (at Løve-1)	Very good

Interpretation of the seismic data show that the seismic tie between the Jelling-1 and Løve-1 wells to the south and the Horsens-1 well to the north is complicated by the presence of a number of faults and fault systems, which disturb and interrupt the seismic continuity in the area.

Consequently, acquisition and interpretation of new seismic data is needed before more reliable maps can be constructed. All maps presented herein are based on the current seismic interpretation and generated from 500x500 m grids.

Due to the lack of sufficient good-quality data near the area of interest, it is difficult to map the precise location of the major faults, the continuation of the top Bunter reflector, the variations in depth and thickness and to predict possible lateral changes in the lithology in the Horsens area. The seismic resolution is not good enough to define and correlate individual sandstone layers within the seismic sequences.

A seismic reflector, corresponding to the top of the Bunter Sandstone Formation, can be correlated to a lithostratigraphic pick in the recently drilled Løve-1 and Jelling-1 wells. The Jelling-1 and Løve-1 well data led to adjustments of the previous seismic interpretation in the Jelling/Løve area, but the extra well data do not substantially affect the existing seismic interpretation (TWT) of Top Bunter Sandstone Formation in the Horsens area.

5.2 Depth-conversion and depth structure maps

An accurate depth-conversion, i.e. the conversion from seismic two-way travel time into structural depth, is difficult due to limited velocity data. Available data only exist from the Jelling-1, Løve-1 and Rønde-1 wells, but the Løve-1 data are considered erroneous (or unreliable) and accordingly left out of the calculations. As a consequence of the sparse data, it was decided to depth-convert the two TWT maps on the basis of a time-depth relationship derived from the Jelling-1 velocity survey (Fig. 12). The updated structural depth maps are included as Enclosure 1 (Top Gassum Formation) and Enclosure 2 (Top Bunter Sandstone Formation).

The velocity data from Jelling-1 are recently added to the GEUS database, resulting in a revised velocity model for the greater Horsens area which forms the basis for producing updated depth structure maps.

5.3 Results of seismic re-interpretation

The result of seismic re-interpretation and the subsequent depth-conversion is presented in two updated depth structure maps, specifically a Top Gassum Formation depth map and a Top Bunter Sandstone Formation depth map (Enclosure 1 and 2). The updated Top Gassum depth map is expected to have an uncertainty of ± 10%, whereas the updated Top Bunter depth map is associated with significantly higher uncertainty (*c.* ± 15% corresponding to *c.* ± 300m).

The position and orientation of a number of pronounced faults are included on the maps; note e.g. the prominent fault zone southwest of Horsens city. Acquisition of new seismic data is needed before a more thorough assessment of fault occurrence and fault density can be carried out.

In the Horsens area, the top of the Bunter Sandstone Formation is expected to be located at 1900–2200 m below MSL, depending on the area in question (i.e. the city area, an area close to Horsens-1 or the surrounding area to Horsens city; refer to Enclosure 2). However, the updated depth structural map of the Top Bunter Sandstone Formation is *still* associated with considerable uncertainty in the Horsens area due to the limited amount of velocity data originating from wells outside the Horsens area. The updated depth map suggests that Top Bunter Sandstone Formation is located at a shallower level than previously mapped by GEUS (see e.g. Mathiesen et al., 2009). The depth map presented in Mathiesen et al. (2009) prognoses a depth of *c.* 2400m for the top of the

Bunter Sandstone Formation at Horsens-1. The velocity model that was used for calculating the latter depth is herein considered to be less valid for the Horsens area, because it presumes the presence of a very thick high-velocity chalk layer like in the Rønde-1 well.

The poor seismic data coverage in the Horsens area along with the presence of several seismic lines of low data quality makes it difficult to generate reliable thickness maps (time isochore maps), but the seismic data currently available (see Fig. 2) give an indication of the variation in formation thicknesses.

With respect to the Gassum Formation, the gross thickness encountered in the Horsens-1 well (94m) is probably representative of areas situated east and west of the well location, but probably also an area west of Horsens city (Figs 8–11). Furthermore, the seismic interpretation indicates that the Gassum Formation thins toward the south and in south-westerly direction relative to the Horsens city area (Fig. 10), and moreover the formation is very thin or absent in the Jelling-Løve area as shown in Enclosure 1.

With respect to the Bunter Sandstone Formation, the gross thickness encountered in Jelling-1 (115m) is probably also representative of areas situated west (and east) of the Horsens-1 well or more specifically, the formation thickness is expected to be 100–200m. However, the Bunter Sandstone Formation thickens in a south-westerly direction relative to the Horsens-1 area (cf. Fig. 10) – and the formation also thickens north of the Horsens-1 well location. The thickness of the Bunter Sandstone Formation varies considerably in the Jelling-Løve area.

6 Temperature assessment

As the existing Danish onshore subsurface temperature database is limited and contains values from wells measured at different depths and at different times, estimated geothermal gradients are fairly uncertain. The database contains somewhat odd values, which are considered to be caused by measurement errors, poor corrections or local geological features e.g. salt structures, limiting the available number of reliable data points even further.

A low geothermal gradient often corresponds to positive structural basement elements, while high values are found in deep sedimentary basins. Therefore, an elongated zone of minimum gradients is found over the Ringkøbing-Fyn High, while maximum values are found in the North Sea area. Considering the onshore area, the gradient varies from 28ºC/km to less than 20ºC/km, and the temperature data have previously been evaluated by Balling et al. (1992, 1994). The wells with temperature data located in the vicinity of the study area are listed in Table 6 (Balling et al., 1994):

Table 6: Temperature data from wells near the Horsens area

Well	$Temp_{HORN}$	$Temp_{csm}$	Top_m b.GL
Horsens-1		44,0	1727,0
Rønde-1	103,2	107,9	4057,0
Rønde-1	113,3	118,5	4893,0
Rønde-1	140,1	140,3	5293,0
Gassum-1		116,0	3028,0

As no temperature data exist from the Jelling-1 and Løve-1 wells, temperature data from the Horsens-1, Gassum-1 and Rønde-1 wells are used and compared to a regional gradient of ~28ºC/km (Fig. 13). The $Temp_{Horn}$ value represents the Horner-corrected bottom hole temperature, while the $Temp_{csm}$ value is a modelled value based on the "cylindrical source method" (see Balling et al., 1994).

In Figure 13, the temperatures are plotted together with a linear temperature prognosis assuming a surface temperature of 8ºC. Notice a more optimal match of the Horsens-1 and Rønde-1 data resulting in a lower gradient (~24ºC/km; red line on Fig. 13). Assuming that the top of the **Gassum Formation** is located 1450m below mean sea level, the formation temperature can be estimated to ~43ºC, if the lower gradient is applied, but ~48ºC when using the regional gradient; both with an uncertainty of ±10%.

If the temperature data from Table 6 are extrapolated to the expected depth of the top **Bunter Sandstone Formation** in the study area, the estimated formation temperature turns out to be ~56ºC (or ~64ºC when using the regional gradient), assuming that the depth to the top of the Bunter reservoir is *c.* 2000m b.MSL (i.e. north of Horsens city).

7 Conclusions and recommendations

A combined evaluation of log data, core data and cuttings samples from the Horsens-1 well indicates that the Gassum Formation contains fine to medium-grained sandstones, which have a net sand thickness of approximately 28 m, an average porosity of *c*. 26% and a corresponding gas permeability of *c*. 500 mD, when a porosity cut-off of 15% is applied. The net-to-gross ratio for the Gassum Formation in Horsens-1 is in the order of 0.30. Furthermore, the transmissibility is reasonably high and presumably, the Gassum Formation forms a potential geothermal reservoir in the Horsens area, as the geological succession encountered in the Horsens-1 well is considered representative of a larger area on the assumption that the Gassum Formation is not disturbed by pronounced faulting. The lack of a directly recorded porosity log in Horsens-1 introduces, however, uncertainty on the porosity evaluation. The uncertainty on the porosity determinations is probably 2–4 porosity units (%-points). The uncertainty on the permeability estimates is rather high, because the available core analysis data mainly originate from wells located outside the study area and the core analysis data do not show a clear and well-defined correlation between porosity and permeability (Fig. 3).

In the Horsens-1 well, the sandstone layers of the Gassum Formation consist largely of fine to medium-grained sandstones. Similarly the Bunter Sandstone Formation is dominated by fine to medium-grained sandstones in the Løve-1 well, but fine-grained sandstones in the Jelling-1 well.

The target of the Horsens-1 well was the Gassum Formation and the well was not drilled to the Bunter Sandstone Formation. The presence of a reservoir within the Bunter Sandstone Formation is therefore not confirmed by well data in the Horsens area. However, the seismic interpretation suggests that the Bunter Sandstone Formation is present in the Horsens area, and from GEUS" regional geological model it is likely that the reservoir quality of the Bunter Sandstone Formation is comparable to the good reservoir quality seen in the Jelling-1 and Løve-1 wells. The Bunter Sandstone Formation is envisaged to be located somewhat deeper at Horsens and accordingly, reservoir properties may turn out to be slightly poorer. For further evaluations of the reservoir potential of the Bunter Sandstone Formation at Horsens, GEUS recommend to conduct a more comprehensive regional geological study including, for instance, data from more wells penetrating the Bunter Sandstone Formation and petrographic data from Bunter sandstone cores. It is expected that such a study will make it possible to better constrain the assessment of the reservoir properties of the Bunter Sandstone Formation and to extrapolate the data into the Horsens area with larger confidence.

If the presence of a potential geothermal reservoir in the Bunter Sandstone Formation can be further constrained and verified through a study including a more regional dataset, the exploration risk is considerably reduced in the Horsens area, as the two potential reservoirs (i.e. the Gassum Formation and the Bunter Sandstone Formation) may be tested by the first geothermal well.

The existing seismic coverage at Horsens is very poor and consequently, GEUS strongly recommend the acquisition of additional seismic data in the Horsens area with the objective to delineate the structural position of the Gassum and Bunter Sandstone formations more accurately – and to map out thickness variations of the two formations prior to the drilling of a first geothermal well. Acquisition and interpretation of new seismic data is therefore needed before **more reliable depths and thickness maps** can be generated. The new seismic investigation should **also focus on seismic continuity**, i.e. include assessment of fault occurrence and fault density.

The velocity function needed for converting seismic two-way travel time into depth is uncertain due to the fact that no velocity data are available from the Horsens-1 well and furthermore, the long distance to wells with reliable velocity data (e.g. Rønde-1 and Jelling-1) introduces uncertainty on the depth-conversion at Horsens. Consequently, the current depth structure map of Top Bunter Sandstone Formation is considerably uncertain in the Horsens area compared with the Rønde and Jelling areas. Acquisition of new seismic data at Horsens will not in itself improve the time-depth relation to be used for the depth-conversion, but it is envisaged that new stacking velocities will improve the velocity model.

Conversely, the Top Gassum depth structure map is less uncertain as the Horsens-1 well penetrates the top Gassum surface and a control point thus exists – the control point corresponds to the top of the Gassum Formation as encountered in the Horsens-1 well, i.e. 1450m b.MSL.

At Horsens, the expected temperature of the Gassum Formation is about 48ºC ±10% (at 1450m), and approx. 64ºC ±10% (at 2000m) for the Bunter Sandstone Formation, when the regional temperature model is applied for both formations.

8 A stepwise general procedure for maturation of an area with geothermal potential

The data from the Danish subsurface have shown that large areas are suitable for geothermal exploitation. If a given area, a geothermal prospect or a local urban area is selected for possible exploitation of the subsurface geothermal energy, the following elements should be considered stepwise to minimize the exploration risks that are related to the geological uncertainties regarding the composition and the structures of the subsurface:

1) **Preliminary geological model.** Establishment of a preliminary geological model based on existing local data (to the extent they exist) combined with GEUS´s regional geological models.

1a) If non-released seismic data exists in or near the study area, it is recommended that the geothermal license holder investigate if access to the data can be obtained in order to strengthen the seismic mapping.

2) **Seismic Acquisition**. If the preliminary geological model is satisfying and predicts that the geothermal potential is sufficient for utilization, the next step will be to acquire a sufficient amount of new seismic data. Based on the integrated dataset comprising the previous and the new data, a new and updated detailed seismic mapping of the local area shall be carried out in order to investigate in more detail the reservoir continuity, presence of faults and, if the data resolution allows it, mapping of possible lateral and vertical variations in lithology. An updated geological model based on step 1 and 2 is then constructed.

3) **Preliminary Reservoir simulation**. If the updated geological model based on the previous and new data set predicts that potential reservoirs exist in the study area, a preliminary flow simulation of their production properties should be carried out. This will calculate the amount of water that may be exploited from the assumed reservoir(s).

4) **Well prognosis**. If the updated geological model and the reservoir simulation are satisfactory with respect to the presence of one or more reservoirs with high-quality sandstones and a sufficient geothermal potential, distance to faults etc., the next step should be to establish a proper drilling

prognosis for a geothermal exploration well including depths, thickness, net/gross ratios and formation geochemistry.

5) **Exploration well**. If the exploration well encounters suitable reservoir(s) as prognosed, pumping tests should be conducted to clarify if enough warm water can be produced from the potential reservoir sandstones.

6) **Evaluation of exploration well**. The encountered stratigraphy should be evaluated with focus toward the reservoirs, and their quality should be assessed from log-evaluation and interpretation of test results. The results are compared with the geological model, well prognosis and the reservoir model; if necessary, the local geological model and the reservoir model is updated and adjusted. On this basis it is evaluated if the geothermal potential is satisfactory for a continuation of the project toward a geothermal plant.

7) **Detailed reservoir model**. If the project continues, a detailed reservoir model based on all available and relevant data should be established.

8) **Updating of the regional model**. All the new data is integrated and evaluated and GEUS´s regional models are adjusted, if needed, in order strengthening future evaluations.

9 References

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10 Figures

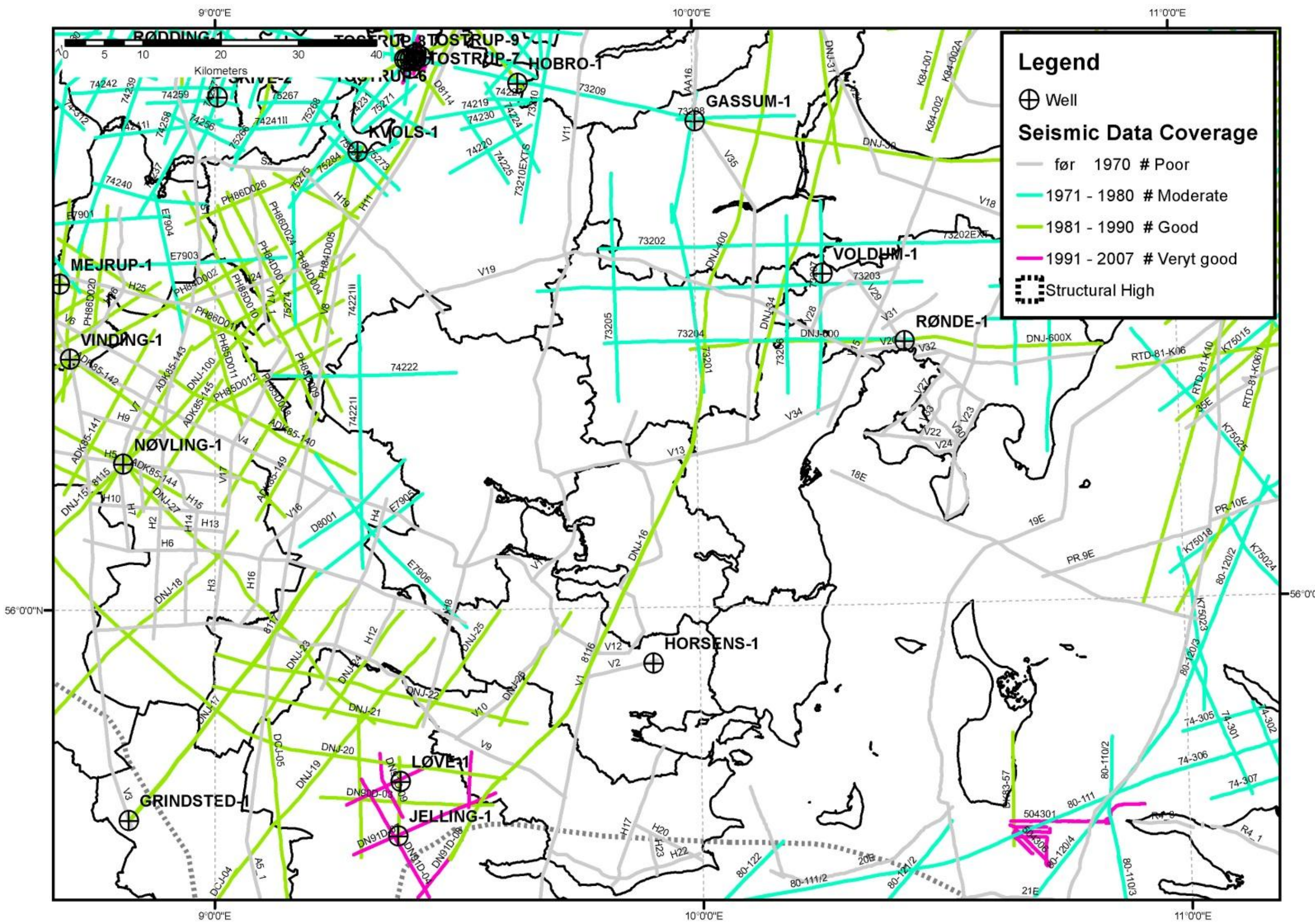


Fig. 1: Map of the greater Horsens area. The map illustrates the seismic data coverage; note that the seismic lines are of different vintages and quality. The locations of the Løve-1, Jelling-1, Gassum-1, Rønde-1 and Horsens-1 wells used in this study are also indicated. The locations of a number of extra wells are also shown.

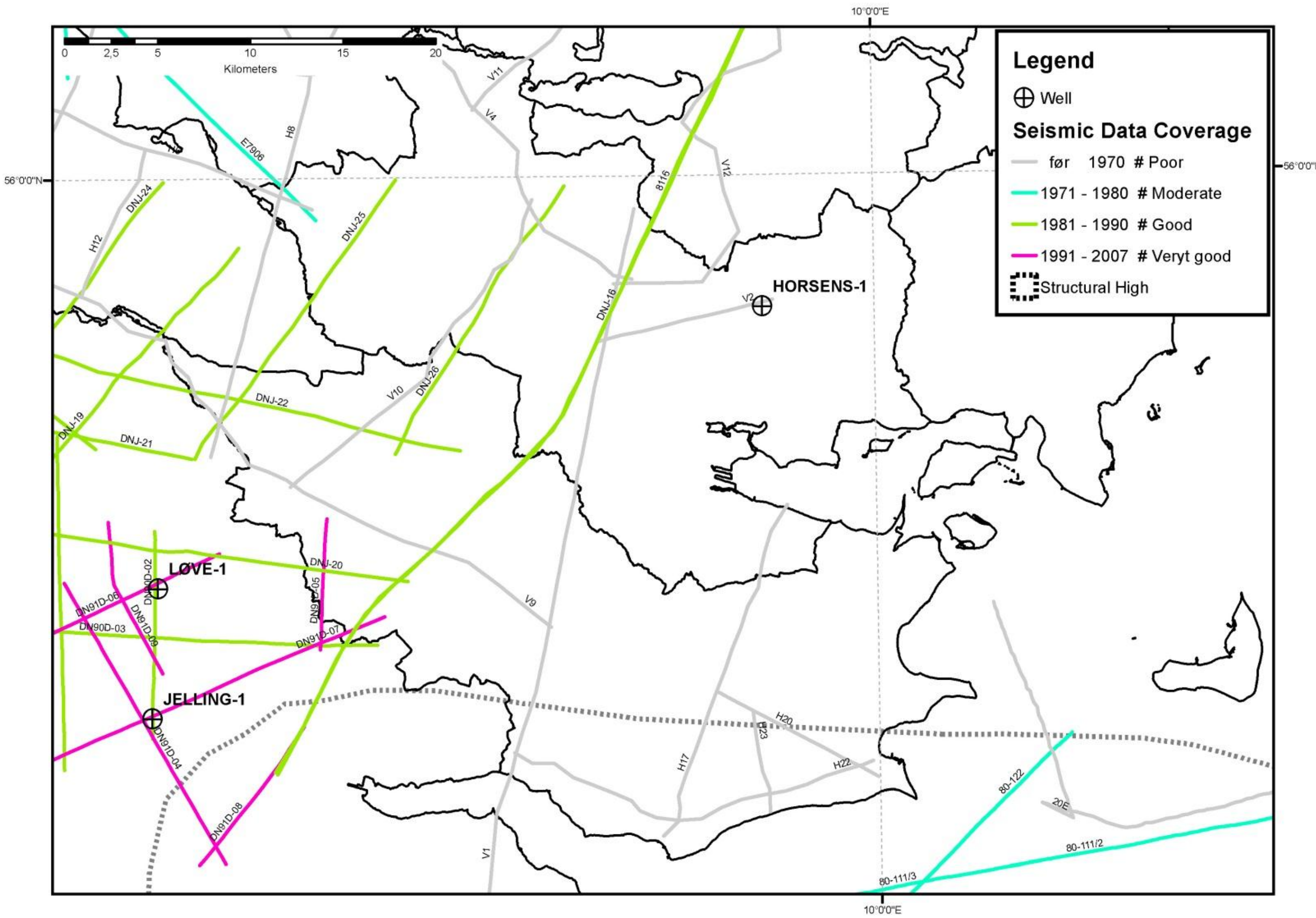


Fig. 2: Map of the area around Horsens; close-up of Figure 1. Note that only one – and rather old -– seismic line passes the location of the Horsens-1 well. No good-quality lines are located close to or around the Horsens city area; this limitation hampers detailed and thorough seismic mapping in the area of interest (corresponding to an area situated in the immediate vicinity of Horsens city).

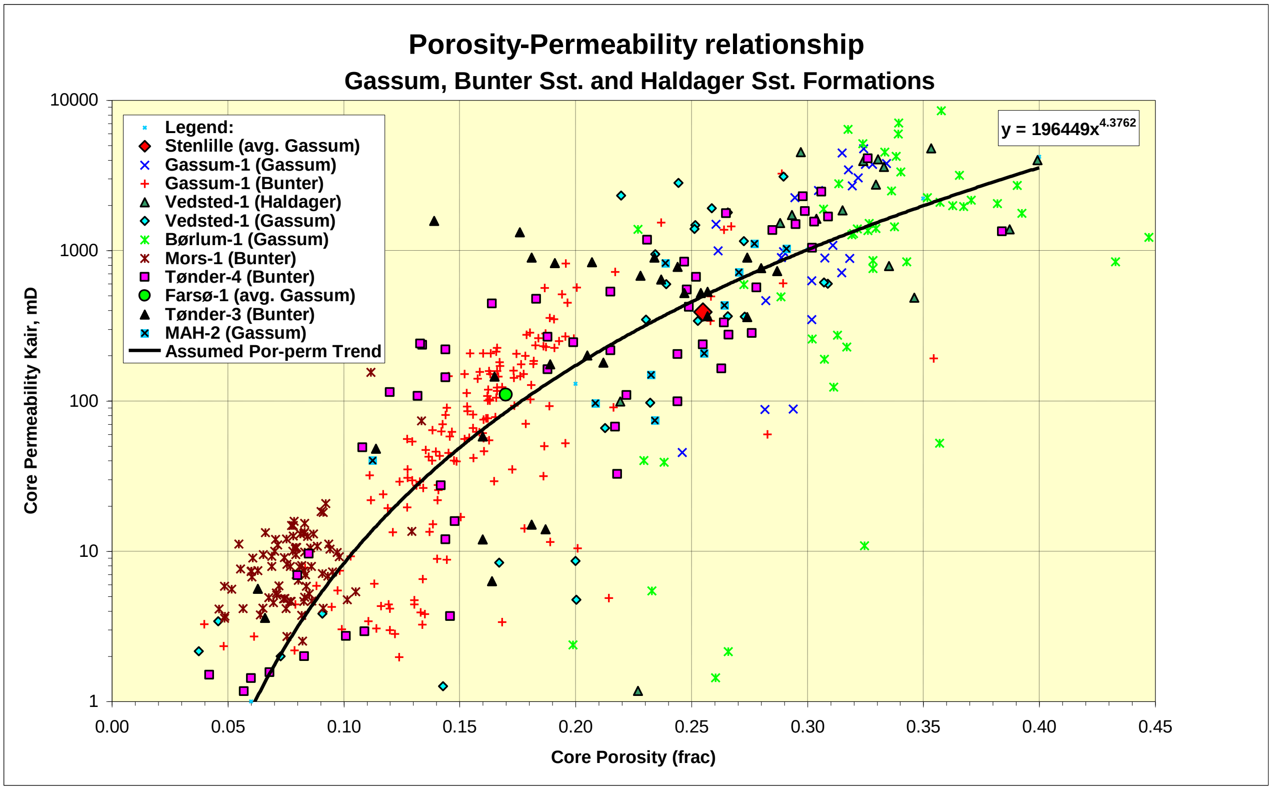


Fig. 3: Generalised relation between porosity and permeability for sandstones based on conventional core analysis data from selected Danish onshore wells in the Danish Basin. The underlying database includes core data from the Bunter Sandstone, Gassum and Haldager Sand Formations. Note that the core permeability data are gas/air permeabilities.

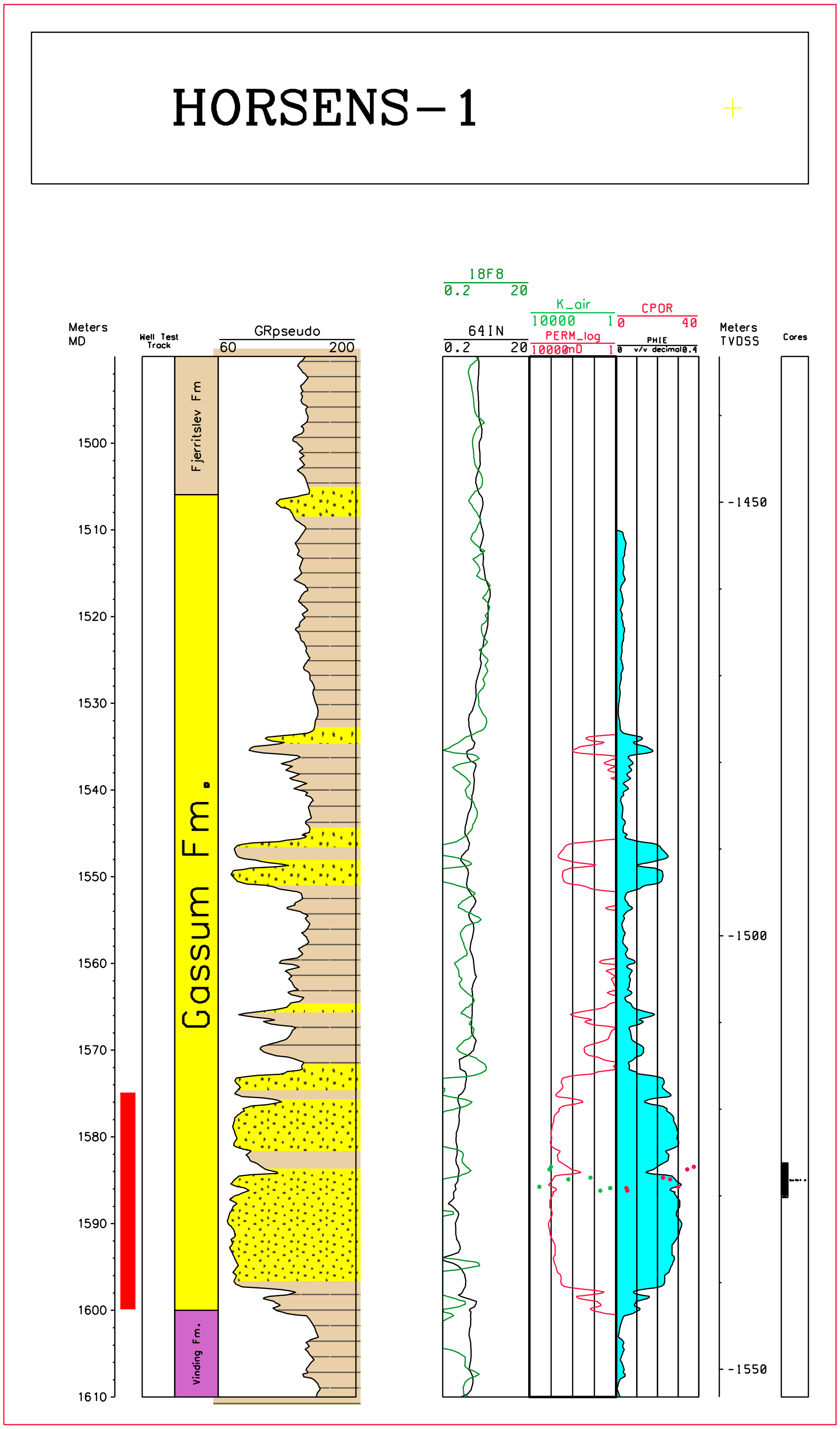


Fig. 4: Petrophysical evaluation of the Gassum Formation in the Horsens-1 well. The location of the main reservoir (*c.* 1573–1597m MD) is indicated by a red bar. Cored interval shown by a black bar; core analysis data plotted by point symbols. Abbreviations are explained in Table 1.

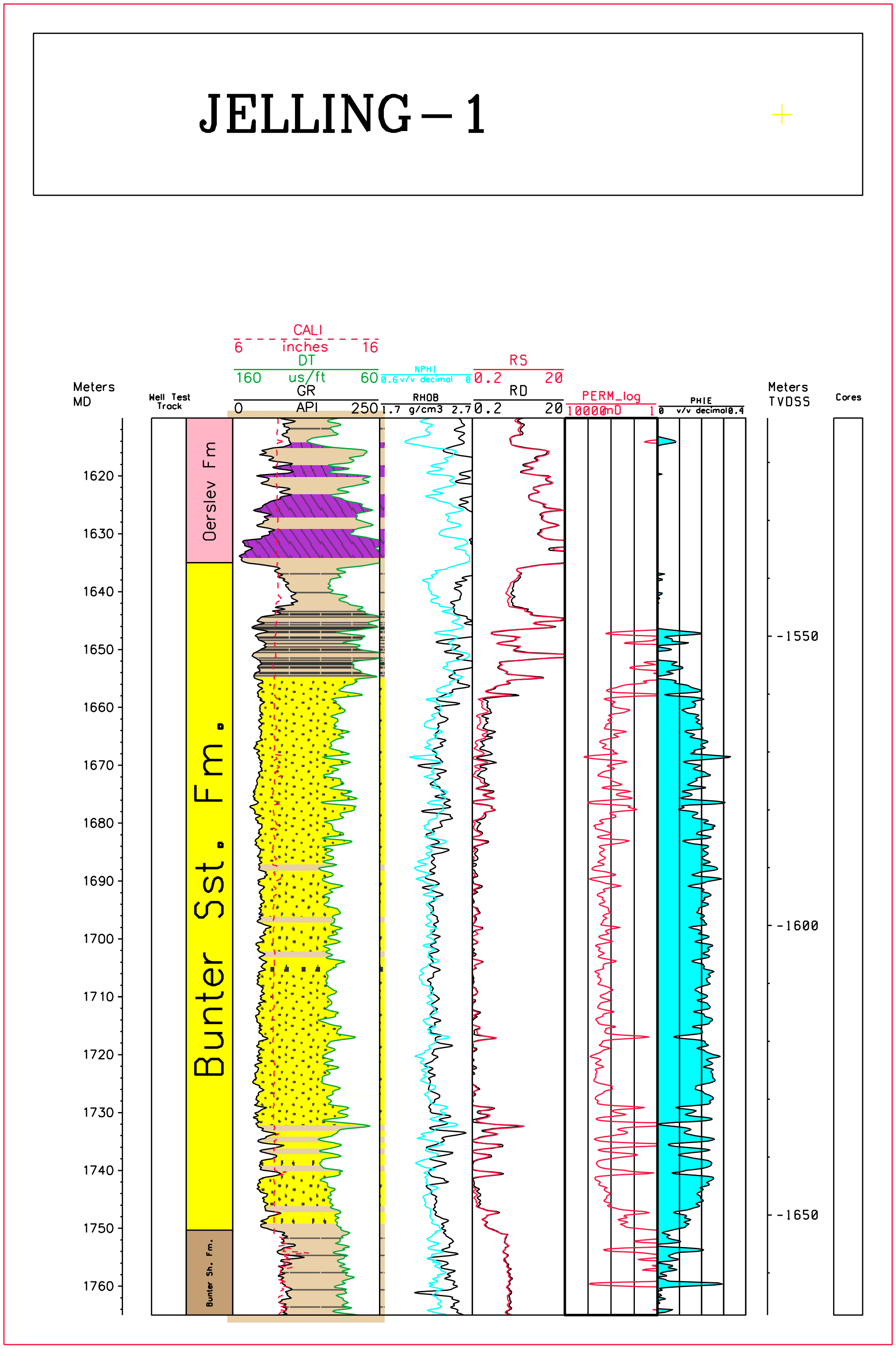


Fig. 5: Petrophysical evaluation of the Bunter Sandstone Formation in the Jelling-1 well. See also Table 1.

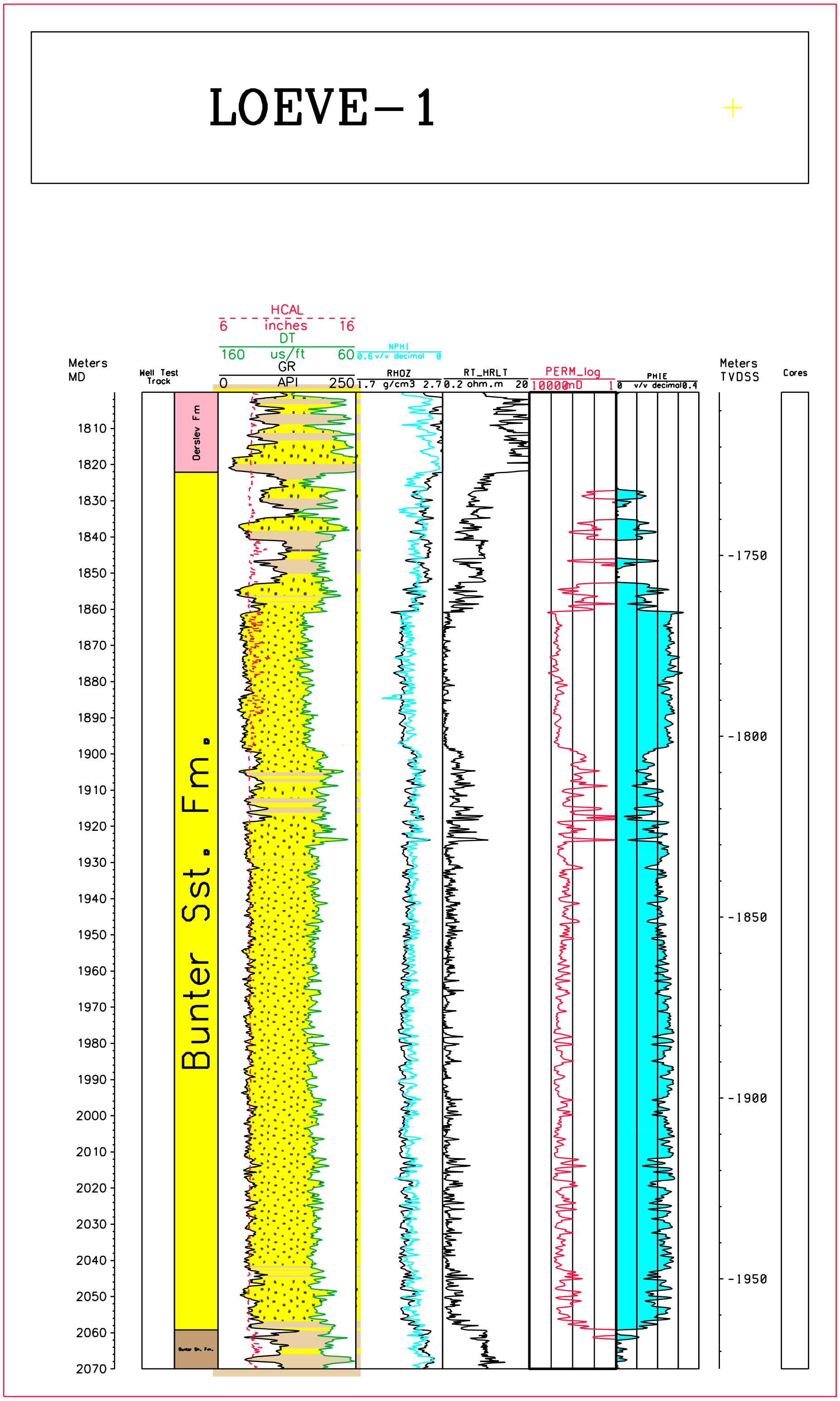


Fig. 6: Petrophysical evaluation of the Bunter Sandstone Formation in the Løve-1 well. See also Table 1.

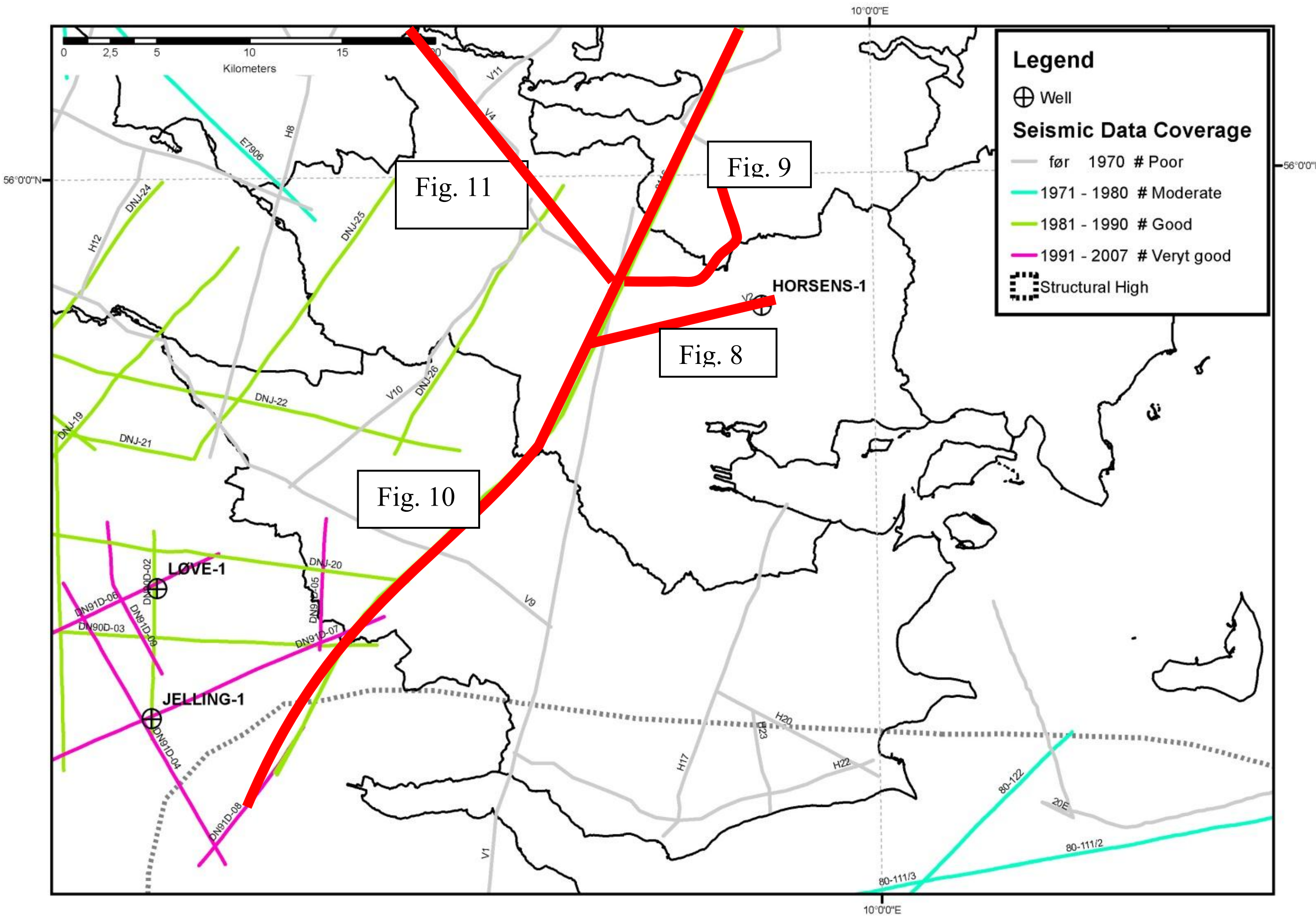


Fig. 7: Map showing the positions of the selected seismic sections shown in Figures 8–11.

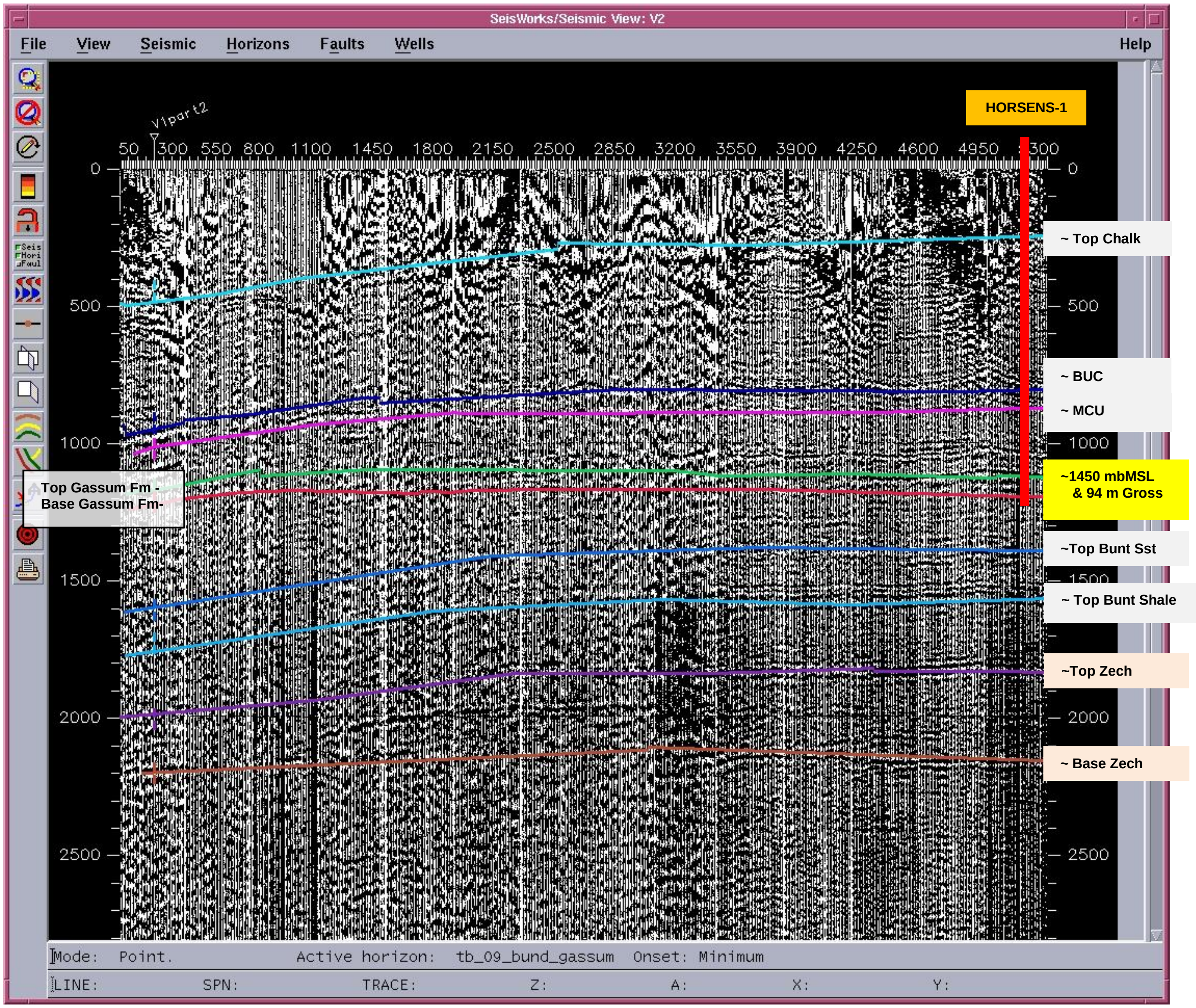


Fig. 8: Seismic section (V2) passing the Horsens-1 well; the location of the Horsens-1 well is only approximate. The seismic data are old and are of low quality and consequently, a reliable interpretation of faults is not possible – some faults may be suppressed and over-looked due the low seismic quality. Interpreted seismic horizons are annotated and plotted in various colours. The near top Gassum Formation horizon is plotted in green, and the near base Gassum Formation horizon in red. The near top Bunter Sandstone Formation horizon is plotted in dark blue; the near top Bunter Shale Formation (corresponding to near base Bunter Sandstone Formation) is plotted in light blue. Compared to the previous GEUS interpretations, the top and base of the Gassum Formation has been adjusted close to the Horsens-1 well. See Fig. 7 for location (left: west; right: east).

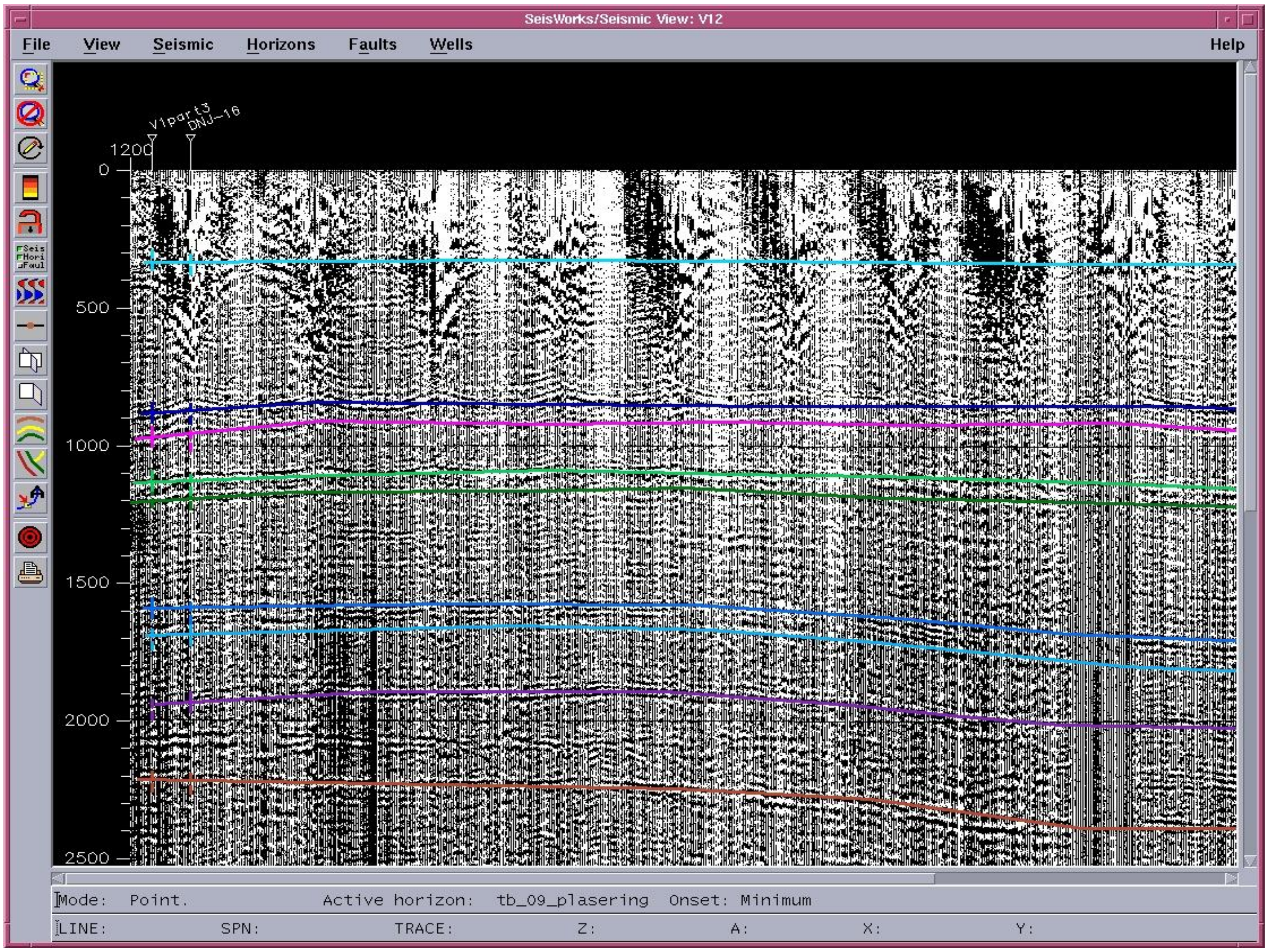


Fig. 9: Seismic section (V12) located NW of Horsens. The seismic data are of poor quality. The section shows, however, reasonably good seismic continuity (no faulting) in this particular area. Near Top Gassum Fm is indicated by light green, Near Base Gassum Fm is indicated by dark green. Near Top Bunter Sandstone Fm is indicated by dark blue, near Top Bunter Shale Fm is indicated by light blue. Seemingly, the thickness of both the Gassum Fm and the Bunter Sandstone Fm is fairly constant. See Fig. 7 for location (left: south; right: north)

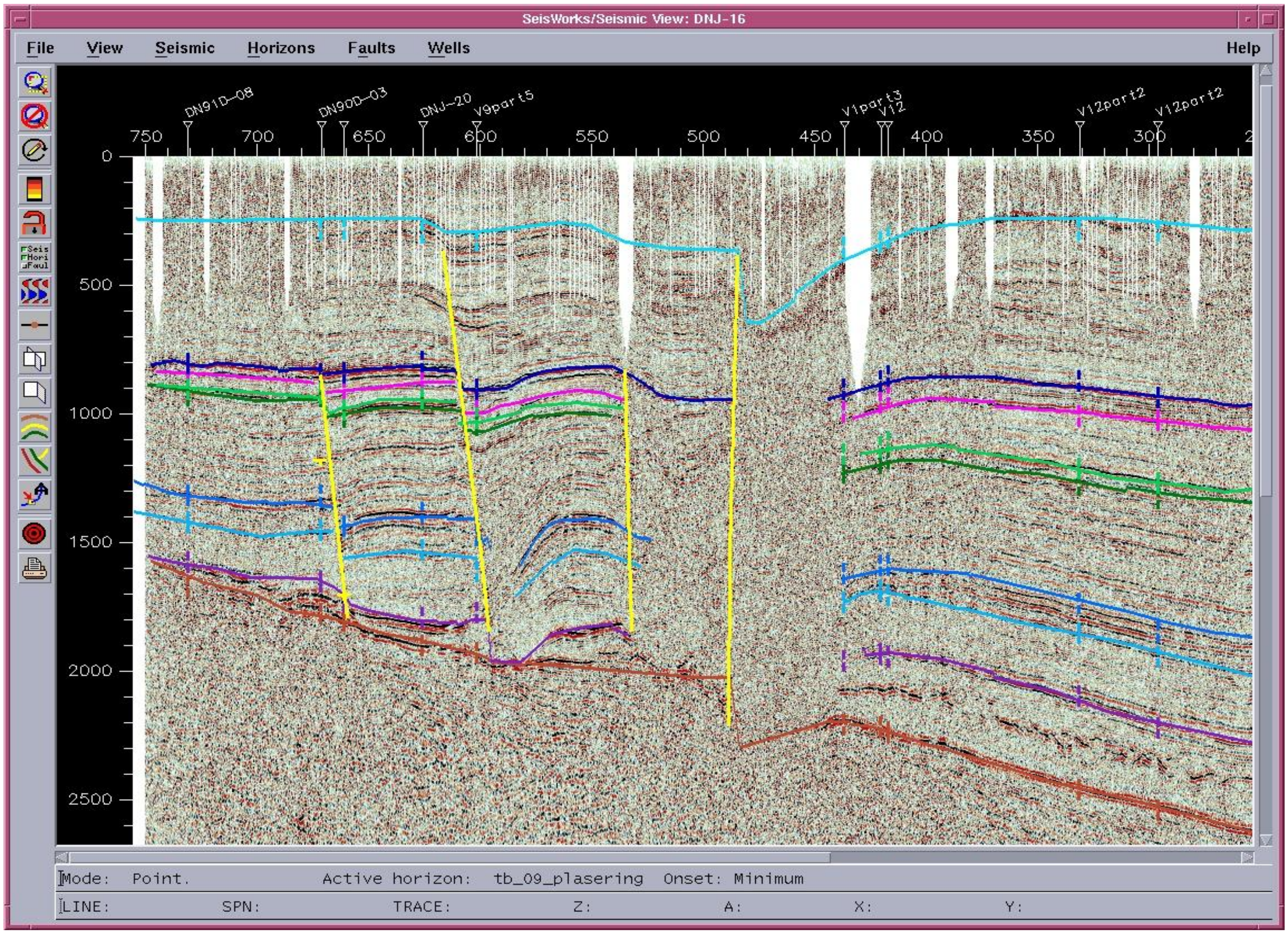


Fig. 10: Seismic section (DNJ-16) showing the presence of fault and fault systems in the area SW of the Horsens-1 well. The seismic data are of good quality. Left part of the section represents an area close to the Løve-1 and Jelling-1wells. The presence of faults complicates a reliable seismic interpretation. A direct tie to line V2 (i.e. the line passing the Horsens-1 well) is not possible due to poor data quality at SP440–480. In general, it is a complex task to tie the Jelling/Løve area to the Horsens area due to faulting and poor seismic data coverage. Near Top Gassum Fm is indicated by light green, Near Base Gassum Fm is indicated by dark green. Near Top Bunter Sandstone Fm is indicated by dark blue, near Top Bunter Shale Fm is indicated by light blue. See Fig. 7 for location (left: SW; right: NE).

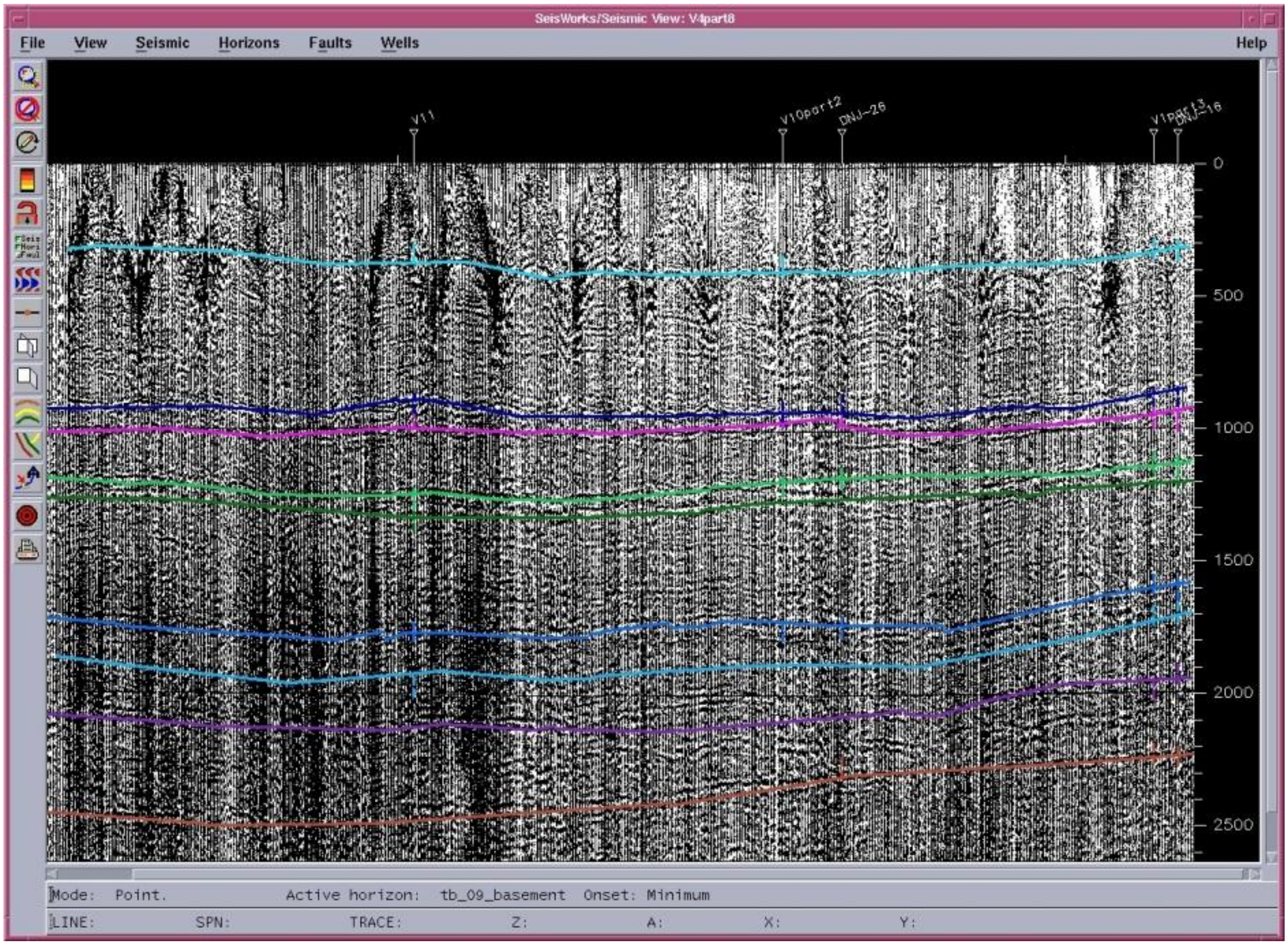


Fig. 11: Seismic section (V4) located NW of Horsens-1.The seismic data are of poor quality. The section shows, however, reasonably good seismic continuity (no faulting) in this particular area. Near Top Gassum Fm is indicated by light green, Near Base Gassum Fm is indicated by dark green. Near Top Bunter Sandstone Fm is indicated by dark blue, near Top Bunter Shale Fm is indicated by light blue. Note that the thickness of both the Gassum Fm and the Bunter Sandstone Fm is assumed to be fairly constant as interpreted from this 2D seismic line of poor quality. See Fig. 7 for location (left: NW; right: SE).

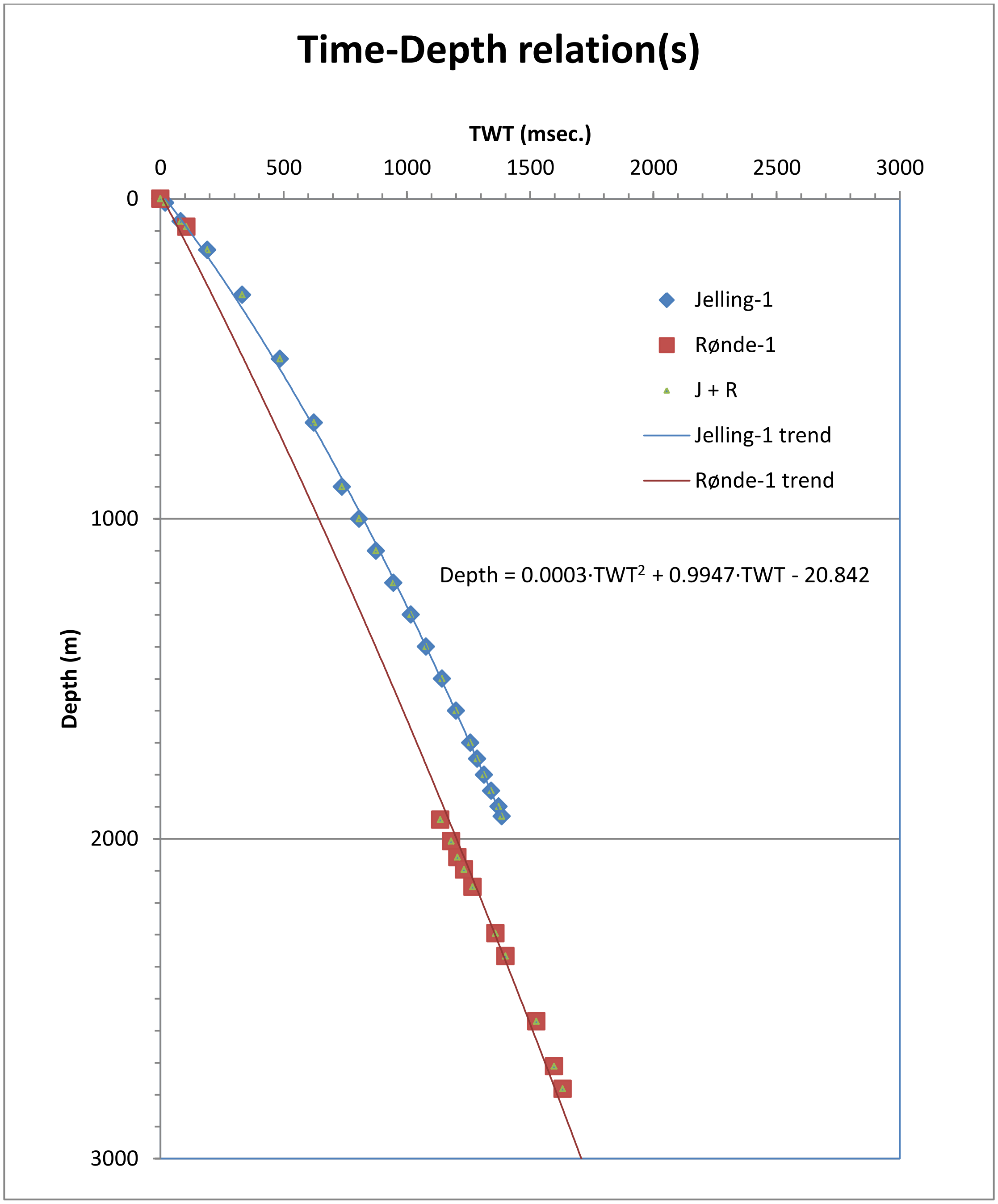


Fig. 12: Time-depth data for the Jelling-1 and Rønde-1 wells. The difference between two trend lines illustrates the uncertainty related to time-depth conversion outside well control. No time-depth data are available from the Horsens-1 well and consequently, a well-defined time-depth relation for the Horsens area cannot be derived.

Area: Horsens area

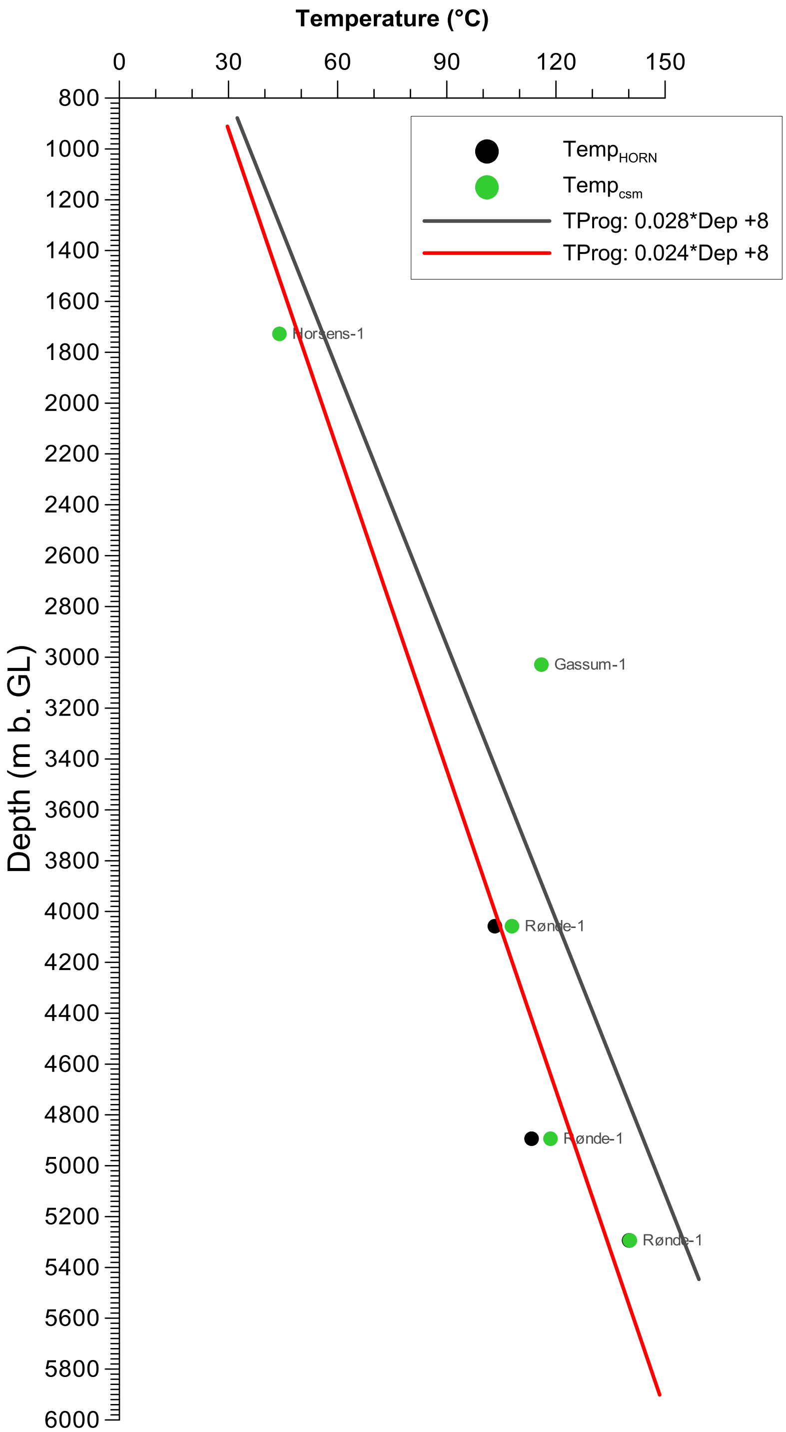
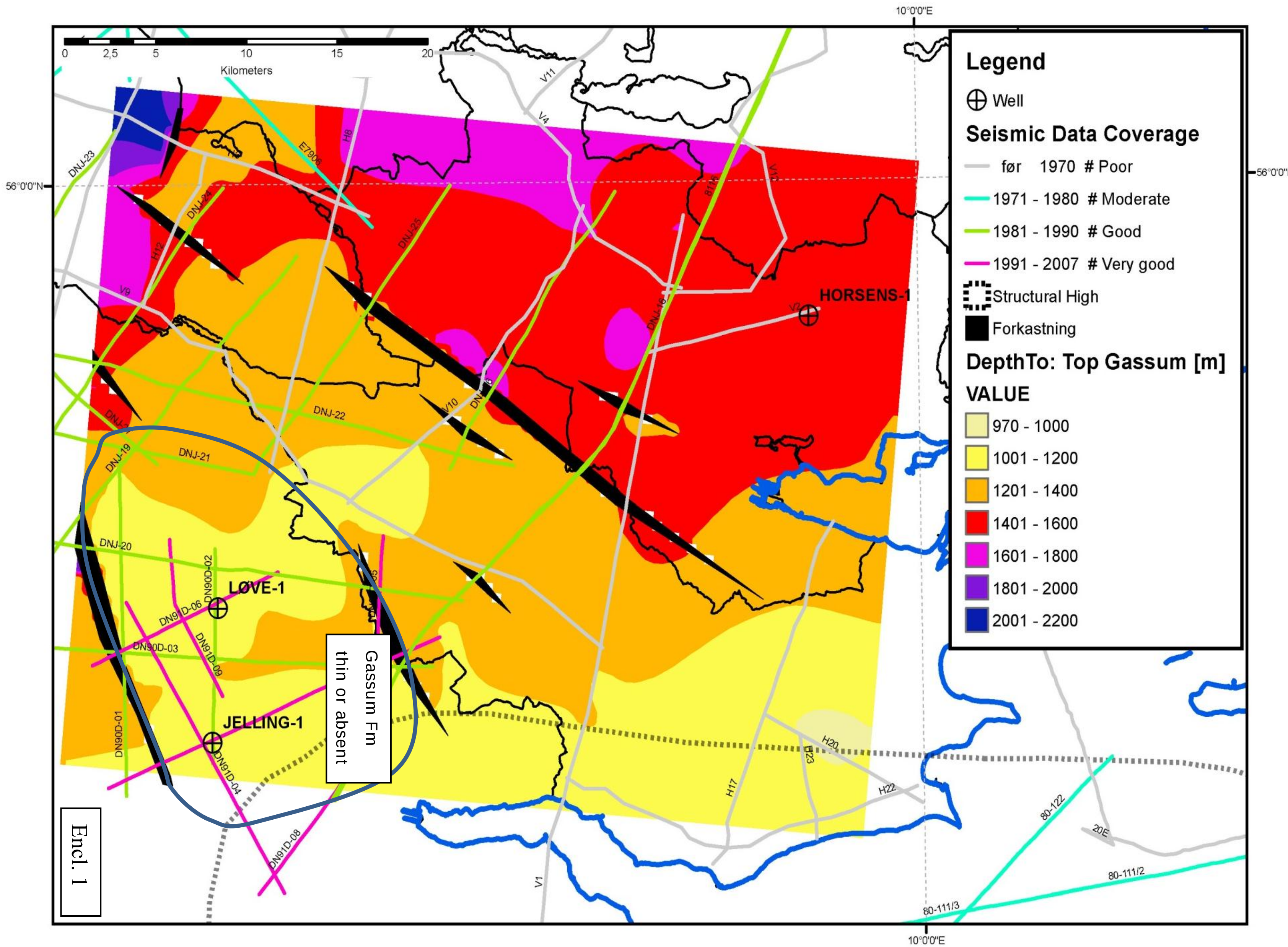


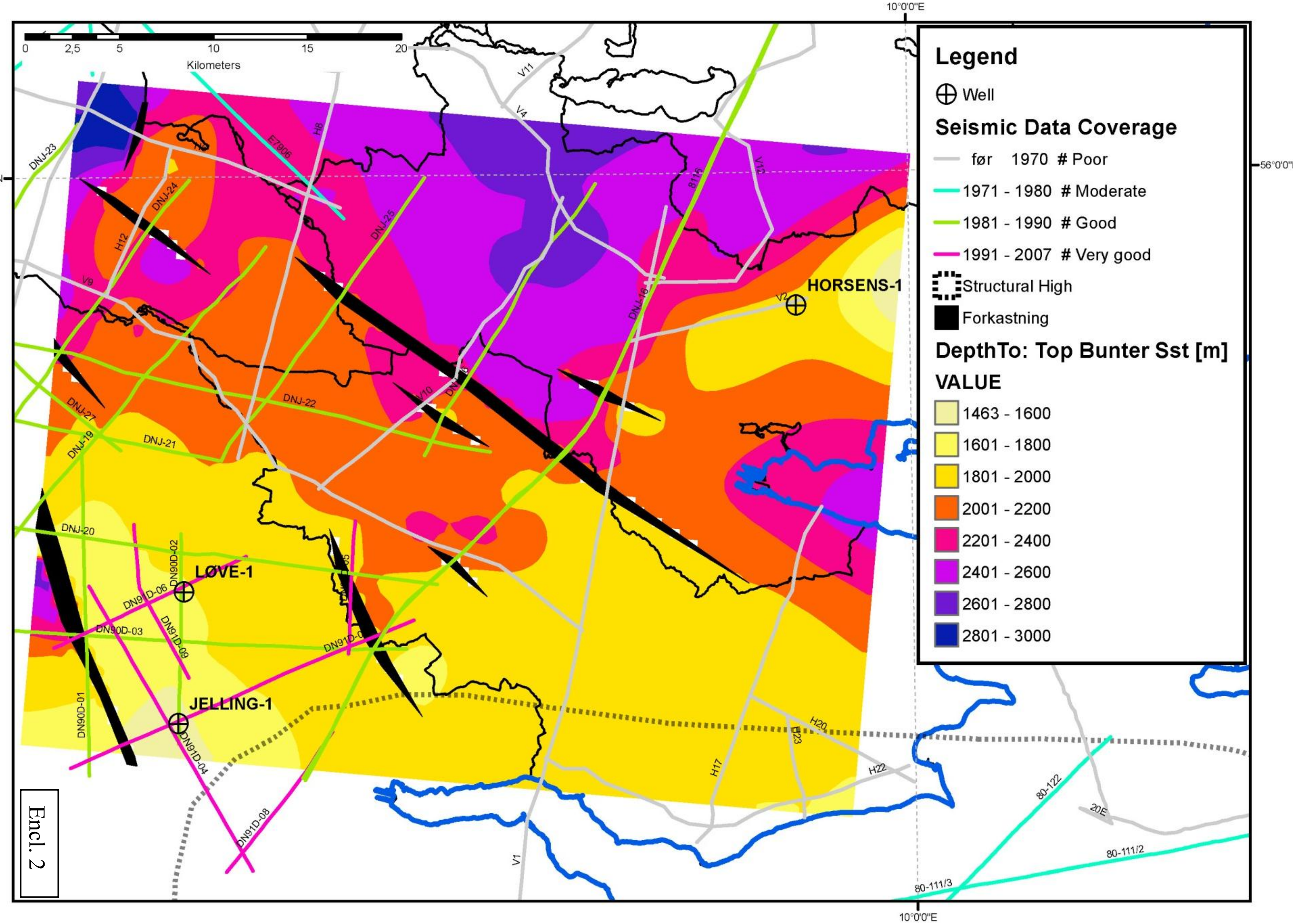
Fig. 13: Temperature prognosis based on available temperature data from the vicinity of the Horsens-1 well. The Gassum-1 outlier is assumed to be an effect of a location near a salt diaper.

11 Enclosures

Enclosure 1: Top Gassum Formation depth structure map, C.I. 200m. Well locations, coast line, position of seismic lines and fault zones are included. The Gassum Formation is thin or absent towards the southwest.

Enclosure 2: Top Bunter Sandstone Formation depth structure map, C.I. 200m. Well locations, coast line, position of seismic lines and fault zones are included


Legend
Well
Seismic Data Coverage
før 1970 # Poor
1971 - 1980 # Moderate
1981 - 1990 # Good
1991 - 2007 # Very good
Structural High
Forkastning
DepthTo: Top Gassum [m]
VALUE
970 - 1000
1001 - 1200
1201 - 1400
1401 - 1600
1601 - 1800
1801 - 2000
2001 - 2200
0 2,5 5 10 15 20
Kilometers
10°0'0"E
56°0'0"N
HORSENS-1
LØVE-1
JELLING-1
Gassum Fm
thin or absent
Encl. 1


Legend
Well
Seismic Data Coverage
før 1970 # Poor
1971 - 1980 # Moderate
1981 - 1990 # Good
1991 - 2007 # Very good
Structural High
Forkastning
DepthTo: Top Bunter Sst [m]
VALUE
1463 - 1600
1601 - 1800
1801 - 2000
2001 - 2200
2201 - 2400
2401 - 2600
2601 - 2800
2801 - 3000
0 2,5 5 10 15 20
Kilometers
10°0'0"E
56°0'0"N
HORSENS-1
LØVE-1
JELLING-1
DNJ-23
DNJ-24
DNJ-25
DNJ-22
DNJ-21
DNJ-20
DNJ-27
DNJ-19
DNJ-16
DN90D-01
DN90D-02
DN90D-03
DN91D-04
DN91D-06
DN91D-08
DN91D-09
E79/06
H8
H12
H17
H20
H22
H23
V1
V2
V4
V9
V10
V11
V12
80-122
80-111/2
80-111/3
20E

Encl. 2