Seismic evidence for deep Palaeozoic sedimentary units in the Ringkøbing-Fyn High offshore Denmark

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Interpretation of refracted and reflected arrivals in seismic data from the MONA LISA combined wide-angle and normal incidence deep seismic experiment in the south-eastern North Sea has revealed deep sediments in the basement high between the Central Graben and the Horn Graben.

Evidence for such deep sediments in the Ringkøbing-Fyn system of basement highs is most clearly found in refracted arrivals in wide-angle seismic data. P-waves refracted in the deep sedimentary units show velocities between ~4.5 km/s and ~5.1 km/s which are significantly below the observed velocities of about 6.0 km/s for crystalline basement. Outline of the shape and fine structure of sedimentary units are constrained by coincident normal incidence seismic reflection data.

A seismic velocity model and a reflectivity section for a 150 km section of the east-west trending MONA LISA line 3 are presented. The velocity model is consistent with both the wide-angle data and the normal incidence section. Pre-Zechstein sedimentary units locally up to 4 km in thickness are observed, and locally the top of the crystalline basement is found at depths of about 7 km to 10 km. The boundary between the deepest sediments and the crystalline basement is characterized by several large block faults. On the flanks of the Horn Graben and the Central Graben a pronounced thinning of the pre-Zechstein sedimentary strata is observed indicating uplift and erosion of rift shoulders.

A correlation between free-air gravity anomalies, local basement highs and deep basins is observed, and the gravity data indicate that Pre-Zechstein sedimentary structures of similar thicknesses are present in the offshore part of the Ringkøbing-Fyn High both north and south of the analyzed seismic line.

Key words: Deep Palaeozoic sediments, Ringkøbing-Fyn High, seismic velocity model, seismic reflections.

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The east-west trending Mid North Sea/Ringkøbing-Fyn system of basement highs was formed during regional tectonic activity in the late Carboniferous-Early Permian (Ziegler 1990). From its time of formation to Early Cretaceous, this system of basement highs remained relatively stable and rigid separating two major areas of Permo-Triassic deposition, the Norwegian-Danish Basin and the North German Basin (Fig. 1). It has been a matter of debate whether or not significant amounts of Palaeozoic sediments exist on the Ringkøbing-Fyn High (RFH).

The interpretation of deep Palaeozoic sediments in the south-eastern North Sea area has formerly been based primarily on commercial seismic reflection sections (Cartwright 1990; Vejbæk 1990 and Vejbæk 1997). In the Horn Graben Abramovitz & Thybo (1998) used wide-angle reflections and refractions to support their interpretation of deep Palaeozoic strata. Similarly, along the N-S trending MONA LISA line 1 Abramovitz, Thybo & MONA LISA Working Group (1998) interpret pre-Zechstein strata based on wide-angle observations. Integrated studies have been car-

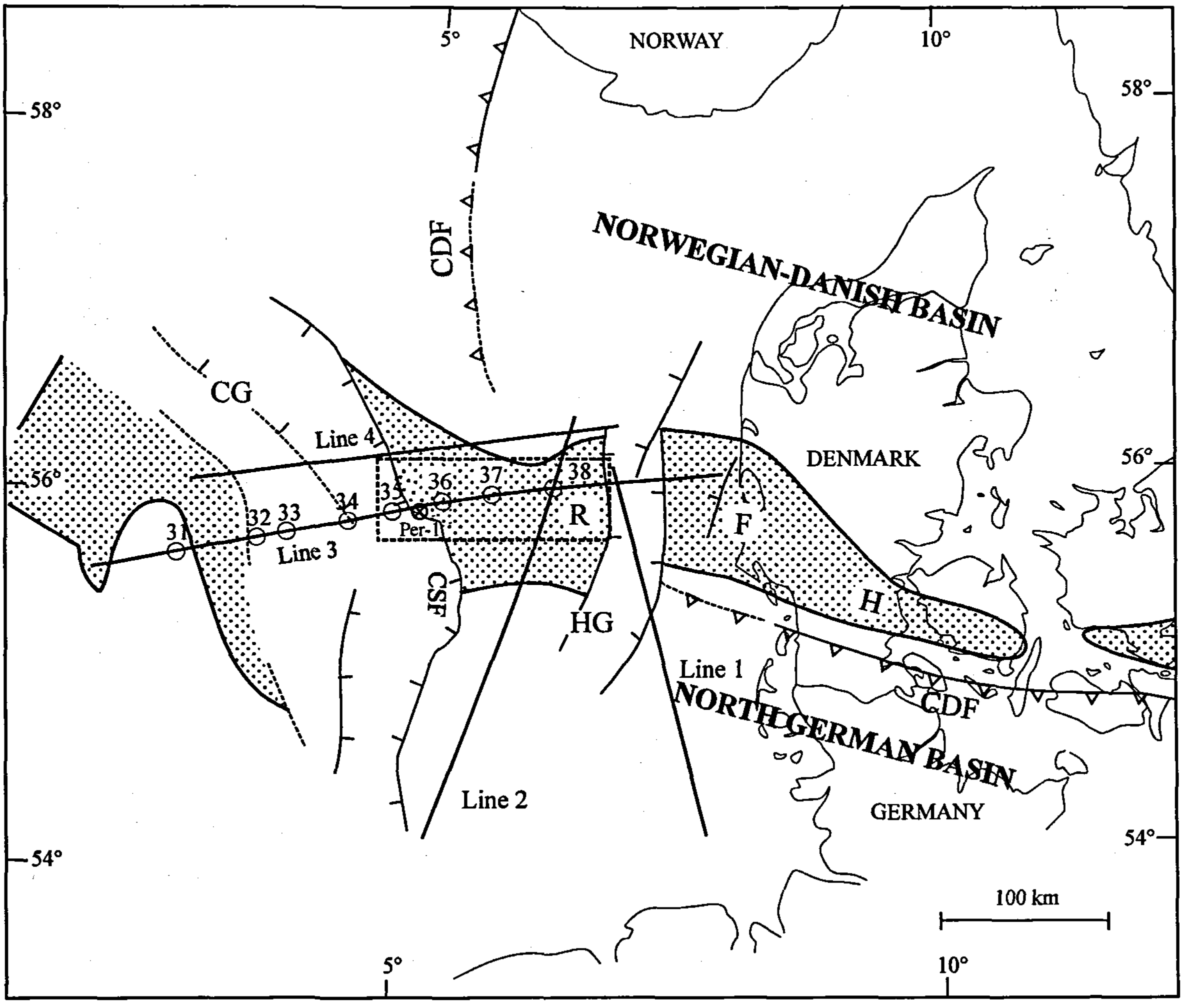


Fig. 1. Map of main structural elements in and adjacent to the study area. The positions of MONA LISA seismic lines (1 to 4) are shown. Wide-angle recording stations (31 to 38) along line 3 are indicated by open circles. RFH: Ringkøbing-Fyn High. CG: Central Graben. HG: Horn Graben. CSF: Coffee Soil Fault. CDF: Caledonian Deformation Front. Open circle with cross between OBH 35 and 36 indicates the location of the Per-1 well. Stippled frame indicates the study area of this paper.

ried out by Zhou & Thybo (1997), who used magnetic data and gravity data to outline the areal extent of Palaeozoic strata in the south-eastern part of the North Sea.

The MONA LISA project, with data acquisition in 1993 and 1995 along four profiles in the central and south-eastern North Sea (Fig. 1) has provided detailed information on crustal and upper mantle structure in areas of the Caledonian Deformation Front (CDF) and the Central Graben (MONA LISA Working Group 1997a, b). From east to west, the MONA LISA line 3 traverses main structural elements in the south-eastern part of the North Sea: The Horn Graben, the RFH, the CDF, the Central Graben and the Mid North Sea High. Seismic wide-angle data recorded by ocean bottom hydrophones (OBHs) along this and other MONA LISA deep seismic lines provide the most detailed velocity information for the crystalline crust and upper mantle so far obtained in this part of the North Sea area. Because of the dense airgun shooting (75 m shot interval for the wide-angle data acquisition) and a good coverage by OBH stations (Fig. 1) the wide-angle sections also contain good velocity information of deep sedimentary layers. Along MONA LISA lines 1 to 3 both wide-angle and normal incidence data were recorded. Thus, integrated interpretation of the two seismic data types is possible along these lines.

The aim of this paper is to document the existence of deep pre-Zechstein sedimentary strata in an area between the Horn Graben and the Central Graben using images provided by seismic wide-angle arrivals recorded by OBHs placed on the RFH and by the coincident deep reflection data. The OBH data provide reverse coverage of upper crustal phases. Thus, good control of the upper crustal velocity structure is provided by the wide-angle recordings. Refracted arrivals show that the up to 4 km thick pre-Zechstein rocks above the top the crystalline basement, locally observed at depths around 7 km to 10 km, have velocities significantly lower than those observed for the crystalline basement. Reflections in the normal incidence section show that the top of the basement, which defines the lower boundary of the pre-Zechstein sedimentary sequences, is block-faulted. These faults introduce travel time anomalies, resembling static time shifts, in arrivals refracted in the upper crystalline crust. Finally, we illustrate that basement topography is reflected in observed free-air gravity anomalies. The gravity data indicate that the deep sedimentary units have a large areal extent on the RFH.

Interpretation and modelling of seismic sections

Wide-angle data

Travel times of refracted and reflected arrivals in the wide-angle sections are interpreted and modelled by use of raytracing and inversion techniques (Zelt & Smith 1992) in order to construct a P-wave velocity model for the sediments and upper crystalline crust of the RFH. The interpretation of the sediment-basement boundary has been supported by the coincident normal incidence section.

Wide-angle data from OBH 36, OBH 37 and OBH 38 have been used to construct the velocity model in the RFH area. Data from the three wide-angle stations are shown in Fig. 2. In all the seismic sections, it is possible to identify two different phases with apparent velocities around 4.5 km/s and 5 km/s, respectively. These phases are most clearly identified when they appear as first arrivals at small offsets (Fig. 2d). However, in some places they can also be correlated as secondary arrivals at larger offsets, where the first arrivals consist of upper crustal refracted phases (P_g) showing apparent velocities close to 6 km/s. The refracted phases with velocities around 4.5 km/s and 5 km/s are interpreted to originate from pre-Zechstein sedimentary units. Due to the difference in P-wave velocity we subdivide these Palaeozoic units into two units, which in the following are referred to as P1 and P2, respectively. A pre-Zechstein sedimentary unit in the Central Graben interpreted to have velocities ranging from 4.8 km/s to 5.6 km/s is referred to as P3.

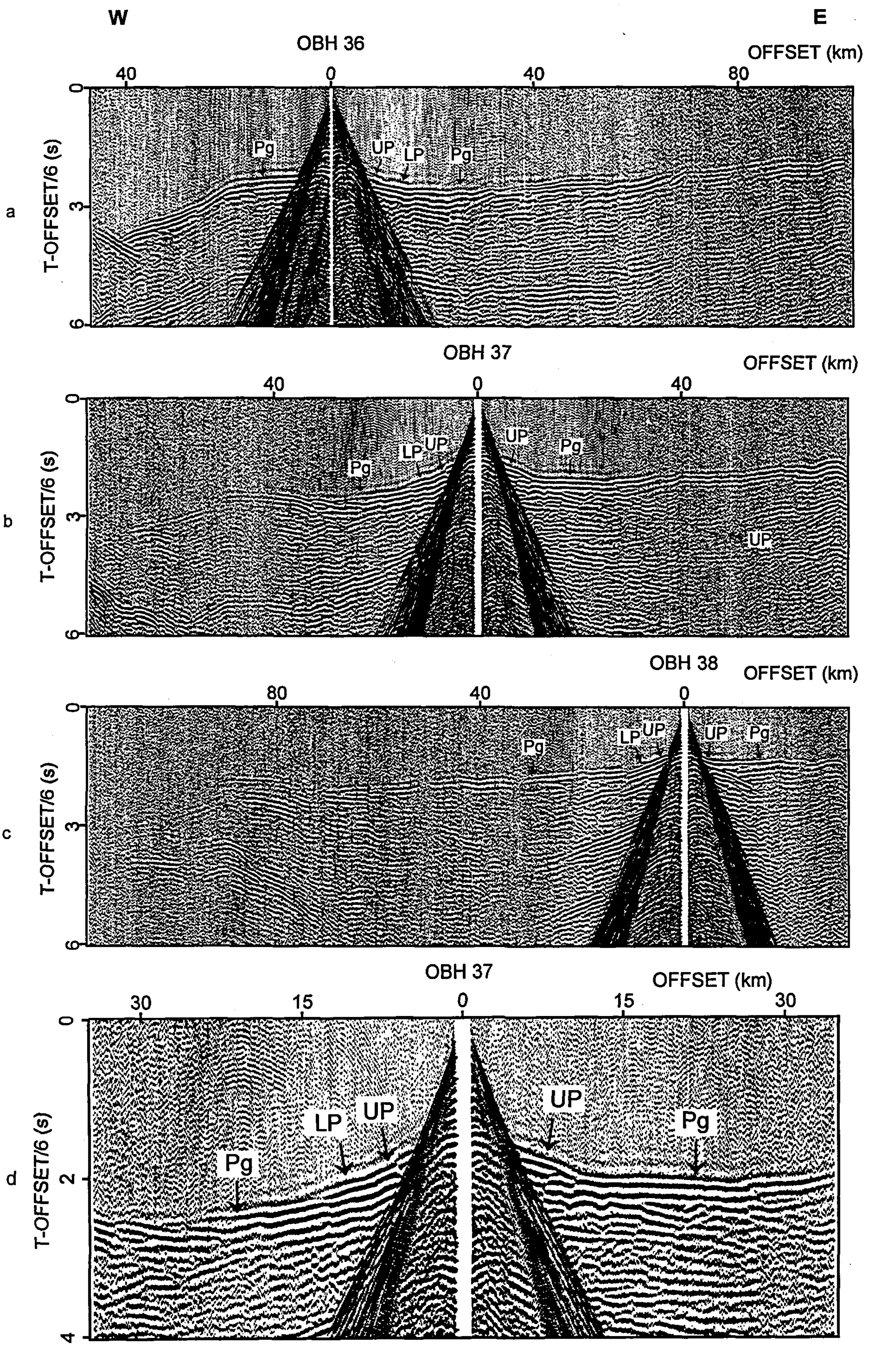
Normal incidence data

The base Chalk Group (BC), top pre-Zechstein (TPZ) horizons and reflections interpreted as top basement have been identified in the MONA LISA line 3 normal incidence section (Fig. 3). The interpretation of the BC and TPZ reflections is supported by well log information (Nielsen & Japsen 1990) and the structural map of Vejbæk & Britze (1994). The BC reflection dips gently from about 1 s twt in the easternmost part of the profile to around 2.5 s in the Central Graben area, and the reflection appears fairly linear throughout the section except in the Central Graben west of the Coffee Soil Fault where inversion tectonics have resulted in some updoming of this interface (Michelsen et al. 1987). In the deepest parts of the Central Graben (the Tail End Graben) just west of the Coffee Soil Fault, the TPZ reaches a maximum depth of 5.5–5.8 s twt. On the RFH only small amounts (i.e. a few hundred metres) of sub-Chalk Group Mesozoic strata are interpreted to exist. The thicknesses of the sub-Chalk Group Mesozoic strata in this area are about the resolution limit of the normal incidence seismic data set.

Although the seismic section is contaminated by large amplitude multiples in the RFH area, reflections which are characterized by low frequencies and interpreted as top basement can be traced over large distances in this part of the section (Fig. 3). However, in some places, the basement reflection is either absent or very weak which suggests that the seismic impedance of the deepest parts of the Palaeozoic strata may be similar to the seismic impedance of the basement. Several normal faults show that the top of the crystalline basement is block faulted. The larger of these faults are also evident as time shifts observed in the P_g arrivals in the wide-angle sections (Fig. 2). The strata between the top pre-Zechstein and the basement are assumed to consist primarily of the two Palaeozoic units mentioned above. Clear, east-dipping reflection patterns inside the Palaeozoic units (indicated by arrows in Fig. 3) may be interpreted as structures related to tectonic activity rather than depositional features. These dipping reflections may indicate the presence of half-graben structures inside the pre-Zechstein units. No clear reflections separating the upper Palaeozoic rocks from the lower Palaeozoic rocks can be identified in the normal incidence data, possibly because the interface between the P1 and P2 units of the wide-angle model may be a velocity gradient zone rather than a first order impedance discontinuity.

Velocity model

A P-wave velocity model for the sediments and upper crystalline basement is shown in Fig. 4. Above the crystalline basement the model is divided into different sedimentary sequences: Cenozoic, Mesozoic, and two Palaeozoic sequences (P1 and P2). In the Central Graben a separate Palaeozoic sequence (P3) has been introduced. Along this profile, the thickness of the Mesozoic sequence is resolved only in the Central Graben where the main rifting and subsidence took place during the Jurassic (Vejbæk 1992). The Palaeo-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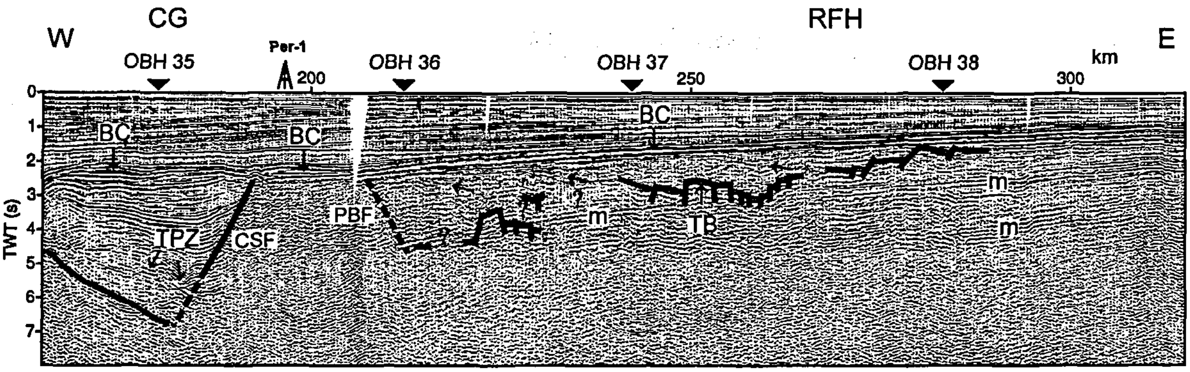

Fig. 3. MONA LISA line 3 normal incidence section plotted to 8 s two-way time. BC: base Chalk Group reflection. TPZ: Top pre-Zechstein reflection. Top basement reflections (TB) are indicated by light shading. m: multiple. CG: Central Graben. RFH: Ringkøbing-Fyn High. CSF: Coffee Soil Fault. PBF: Palaeozoic Boundary Fault. The position of the Per-1 well is indicated. OBH positions 35 to 38 are shown. Arrows indicate dipping reflection patterns inside the pre-Zechstein sedimentary units. The eastern end of the profile terminates at the western boundary fault of the Horn Graben.

zoic units reach their maximum thickness of 4-6 km in the westernmost part of the Palaeozoic sedimentary basin on the RFH, and they gradually thin out in the easternmost part of the profile. The Palaeozoic rocks in P1 have been modelled to have velocities between 4.5 km/s and 4.7 km/s, whereas the Palaeozoic rocks in P2 have slightly higher and fairly uniform velocities between 5.0 km/s and 5.1 km/s. Due to the OBH spacing of 30–40 km, the wide-angle data only provide reversed coverage of the refracted arrivals in the Palaeozoic sediments in a limited part of the model profile. In the western part of the RFH a velocity gradient zone beneath P2, where the velocity increases from 5.1 km/s to 5.8 km/s, has been included in the model. The effect of this ca. 1 km thick gradient zone is that observed travel times can be fitted in regions along the profile, which are not otherwise illuminated by rays. Geologically, the velocity gradient zone may describe the gradual lithological transition from Palaeozoic sedimentary rocks to crystalline basement. The accuracy of the estimated velocities in P1 and P2 are no better than +/– 0.2 km/s. An elevated basement block is situated just east of the Coffee Soil Fault. This locally elevated block is clearly imaged by the wide-angle data. In the data section of OBH 36 (Fig. 2a), which is situated almost directly above the western boundary fault of the Palaeozoic units, the first arrival to the west of the station shows an apparent velocity close to 6.0 km/s already at small offsets (cf. Fig. 2a) indicating basement at shallow depths, whereas the refracted phases in the Palaeozoic units showing smaller apparent velocities become visible to the east.

The velocity model has been constructed by combined forward and inverse modelling of travel times of phases picked in the wide-angle sections mentioned above. The details found in the upper basement surface are in general supported by the normal incidence data, which in further detail are able to resolve the fine structures of the individual layers. The dip of the western boundary fault of the Palaeozoic sediments (PBF, Fig. 3) is also constrained by modelling of energy reflected from the fault zone itself, which can be observed in the wide-angle sections (Nielsen et al. 1998). Modelled rays and the fit of the calculated travel times to the observed travel times of OBH 36 are shown in Fig. 5. A travel time fit to picked phases with a root-mean-square misfit below 60 ms has been obtained for all wide-angle stations, which is satisfactory taking the very inhomogeneous nature of the sediment-basement boundary into account.

By transforming the velocity model into two-way travel time, this model can be directly compared to the coincident normal incidence section. Fig. 6 shows the normal incidence section with travel times of the smoother velocity model superimposed. In the western part of the RFH, where a gradient zone has been included below P2 (see Fig. 4), the travel times of the top basement have been calculated with respect to the top of the gradient zone. The overall characters of the sedimentary boundaries in the normal incidence section and the velocity model are similar, although small scale structures are not resolved in the velocity model.

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Fig. 2. Wide-angle seismic sections of OBH 36 (a), OBH37 (b) and OBH 38 (c), respectively. (d) shows an enlarged plot of the wide-angle section of OBH37. Interpreted phases: refraction in P1 (UP), refraction in P2 (LP), refraction in upper crystalline basement (Pg). Sections are plotted in reduced travel time versus offset (reduction velocity is 6 km/s). Data have been bandpass filtered and deconvolution has been performed. An AGC with an operator length equal to the total trace length has been applied. Weak energy in front of first arrivals is due to filtering effects.

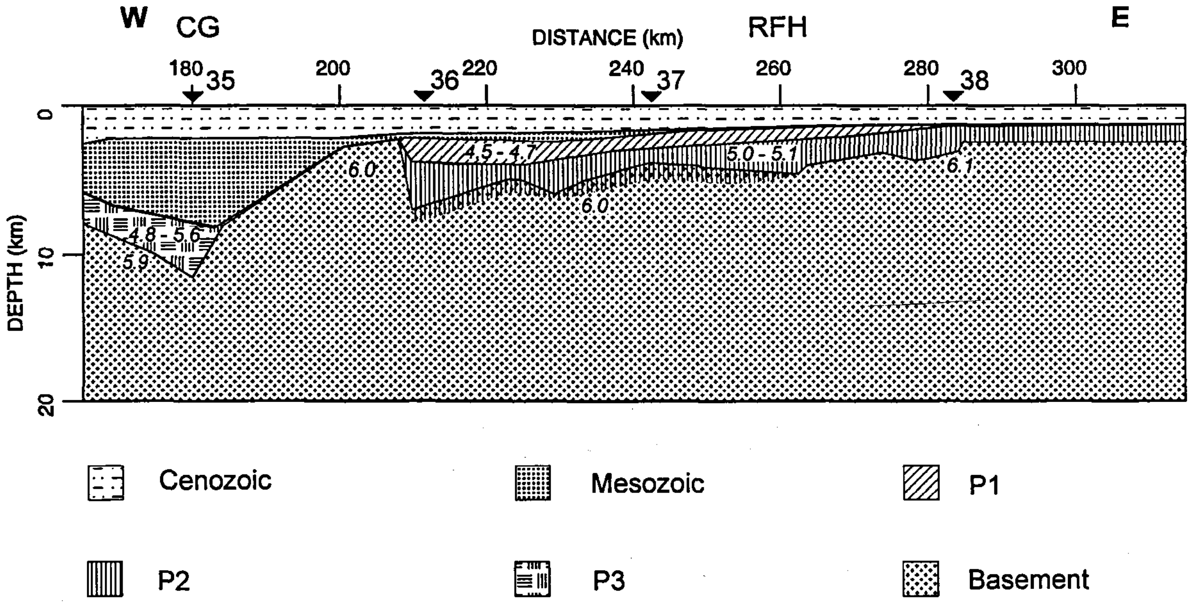

Fig. 4. P-wave velocity model. Velocities (km/s) in P1, P2, P3 and basement are shown. Shaded area marks the position of a gradient zone where the velocity increases from 5.1 km/s to 5.8 km/s. Triangles show the positions of OBH 35 to 38. The eastern end of the model profile terminates at the western boundary fault of the Horn Graben.

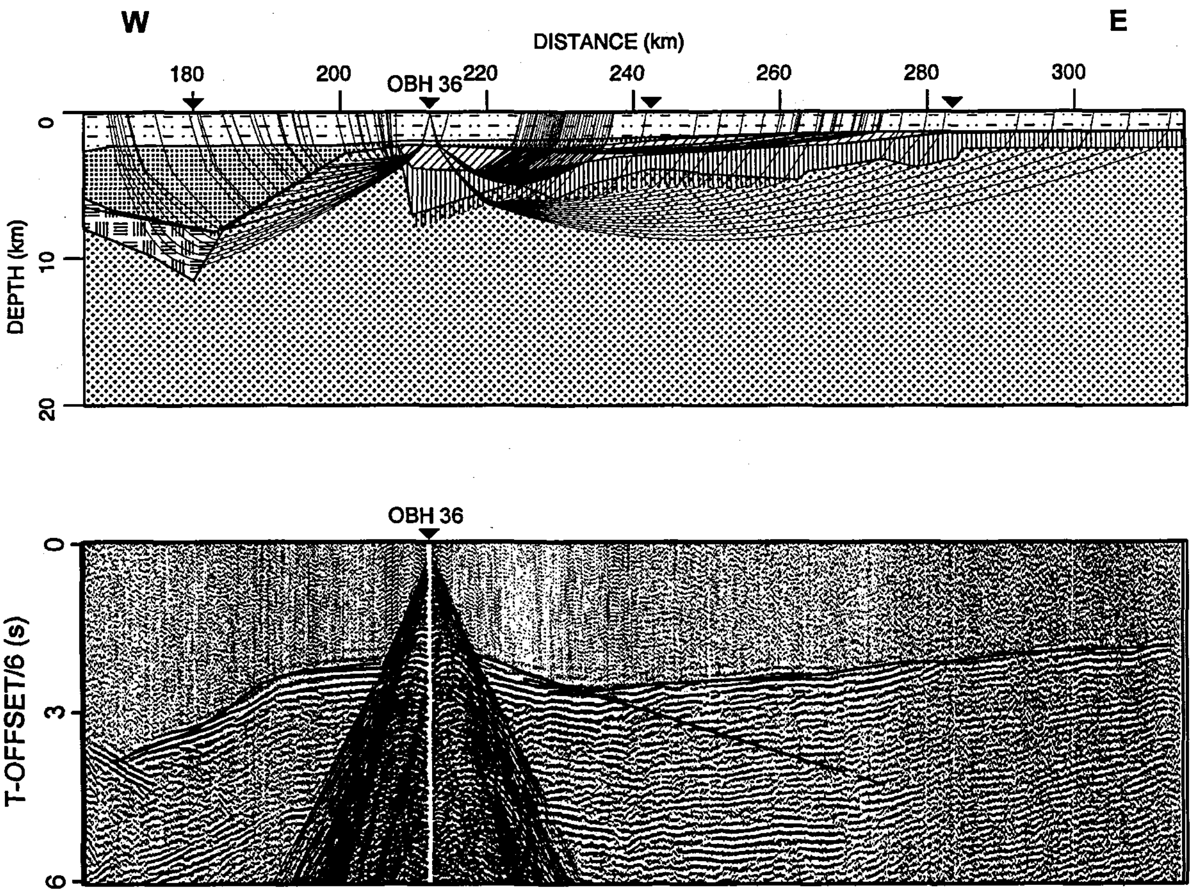

Fig. 5. Rays traced in the velocity model from OBH 36 (top). From left to right the triangles show the positions of OBH 35 to 38. Travel times of modelled phases plotted on top of observed data (bottom).

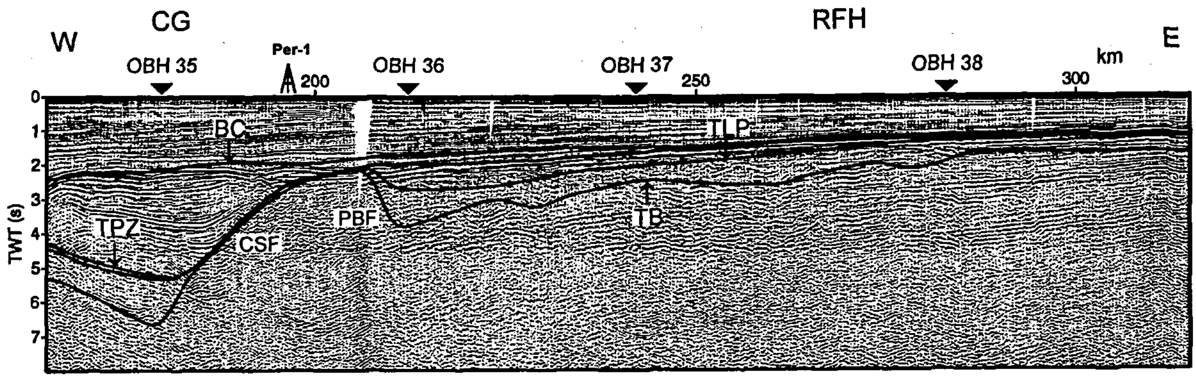

Fig. 6. MONA LISA line 3 normal incidence data section (cf. Fig. 3) with equivalent travel times obtained from the wide-angle velocity model superimposed. Two-way travel times from BC, TPZ, top P2 (TLP) and top basement (TB) have been calculated. OBH positions along line 3 are shown.

Clearly, the largest differences between velocity model and normal incidence interpretation exist on the RFH just east of the boundary fault of the Palaeozoic structures (around km 210), where the normal incidence interpretation tentatively suggests that the top of the basement may be situated 2–3 km deeper than the ~7 km of the velocity model. This difference might be due to the fact that the wide-angle data provide less resolution than the normal incidence data, and the velocity model therefore gives a more smooth picture of the top basement boundary. Also, this particular region is only sparsely covered by modelled ray paths (Fig. 5). Thus, the integrated interpretation cannot give a more precise estimate of the depth to the crystalline basement in this area than the 7–10 km indicated above. In the middle and more eastern part of the RFH and in the Central Graben the same overall trends of the top basement structures can be observed in the normal incidence interpretation and in the top basement of the velocity model.

Free-air gravity anomalies measured in the study area are shown in Fig. 7. The tertiary sediments have an even distribution along the profile with no abrupt lateral changes. Therefore, the tertiary sediments do not introduce short wavelength gravity anomalies, and it is clear that several of the observed gravity anomalies in the RFH area must be caused by lateral density variations at sub-Zechstein levels. In fact, along MONA LISA line 3 a correlation between positive free-air anomalies and pre-Zechstein elevated basement structures is observed: Just west of OBH 36, where the basement is present at relatively shallow depths, and east of OBH 38, where the Palaeozoic strata have thinned out, positive free-air anomalies of

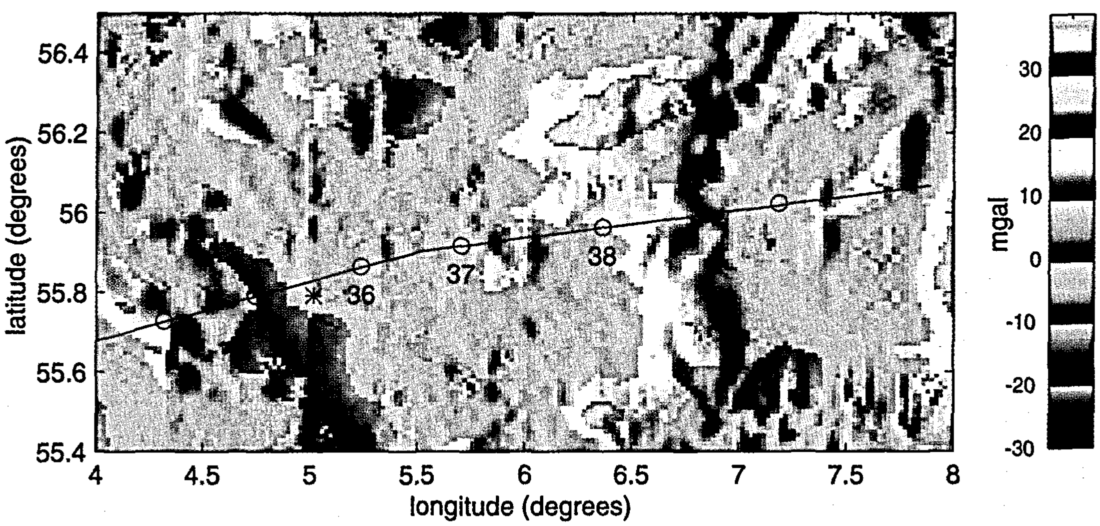

Fig. 7. Observed free-air gravity anomalies (mgal). The location of MONA LISA line 3 and positions of OBH's are indicated. The asterix west of OBH 36 shows the location of the Per-1 well.

up to + 18 mgal are found. As a contrast, negative gravity anomalies down to –7 mgal can be observed in areas of the RFH where the Palaeozoic units reach their maximum thicknesses. Because of this correlation between basement topography and gravity values we suggest thick and deep Palaeozoic sedimentary rocks to be present in the RFH also north and south of MONA LISA line 3, where negative free-air anomalies of similar amplitude are present (cf. Fig. 7).

Discussion

In this integrated seismic study we identify deep pre-Zechstein sedimentary units on the RFH along MONA LISA line 3. The interpretation of these deep sedimentary units is based upon wide-angle data sections and the coincident normal incidence section which mutually support each other. The model presented suggests that Palaeozoic sediments reach depths larger than 5 km corresponding to two-way travel times above 4 s. Other authors (Cartwright 1990; Vejbæk 1997 and Zhou & Thybo 1997) interpret the top basement boundary to be present at the same two-way time level in other parts of the RFH. Thus, if the modelled P-wave velocities between 4.5 km/s to 5.1 km/s are representative for the Palaeozoic sediments on the RFH in general, depths to the top basement up to 5 km are not uncommon in areas where the Palaeozoic sediments reach their largest thicknesses. Observed free-air gravity anomalies also indicate that Palaeozoic sedimentary rocks of thicknesses comparable to the thicknesses modelled along MONA LISA line 3 are present in other parts of the RFH. No wide-angle recordings exist along MONA LISA line 4 (Fig. 1), and similar integrated wide-angle and normal incidence studies cannot be performed along this line. The normal incidence data of line 4 do not unequivocally prove the existence of pre-Zechstein sedimentary units.

In this paper focus has been put on the RFH area, but we have extended our model into the Central Graben area, where deep Palaeozoic sediments are also found. This agrees with seismic observations by Klinkby, Balling & Liboriussen (1998). We model the eastern boundary fault of the Central Graben, the Coffee Soil Fault, to have a dip of approximately 17° down to a depth of 8 km. Below 8 km this fault has been interpreted to become steeper and reach a dip of about 42°. However, from the normal incidence data in Fig. 3 it can also be argued that the Coffee Soil Fault in the area close to MONA LISA line 3 has a less steep shape at depths below 8 km. Klinkby et al. (1998) performed depth migrations of this boundary fault along profile DK88-43, situated about 40 km south of MONA LISA line 3, and found that the Coffee Soil Fault dips approximately 44° down to a depth of ca. 5 km. The apparently low dip angle of the Coffee Soil Fault down to 8 km depth observed along MONA LISA line 3 may possibly be related to the structural setting of the Poul Plateau situated just west of the Per-1 well (Michelsen et al. 1987).

The Per-1 well situated close to the studied profile on the elevated basement block east of the Central Graben bottoms in rocks of Precambrian age (K/Ar age of 857 Ma on pyroxenes) with Caledonian overprint (dated to 435 Ma) (Nielsen & Japsen 1990; Vejbæk 1997). According to MONA LISA Working Group (1997a), west dipping reflectors in the upper crystalline crust which reach top basement level close to OBH 38 (cf. Fig. 1) may mark the approximate position of the Caledonian Deformation Front (CDF). This interpretation of the position of the CDF is in good agreement with results presented by Frost, Fitch & Miller (1981) and Vejbæk (1997). Vejbæk (1997) interprets Lower Palaeozoic sediments to be influenced by Caledonian deformation along the NNE-SSV trending seismic profile SP82-58, which is situated west of the Horn Graben and south of MONA LISA line 3. Thus, we may assume Caledonian overprint in the deeper parts of most of the presented seismic profile. In the normal incidence data, the border between the deep sediments and the top of the crystalline basement in the RFH has a variable character with respect to reflectivity. In most parts of the profile, the top basement reflection appears as a quite clear low frequency event. However, in the western part of the RFH this reflection is absent or at least very weak (see Fig. 3), thus suggesting that the acoustic impedance contrast between the lowest deep sediments and the top of the crystalline basement is small. The areas with reduced acoustic impedance contrast may be interpreted to be areas where the deepest Palaeozoic rocks have been subjected to significant metamorphism due to the Caledonian deformation, which seems to have taken place during Late Ordovician to Early Silurian times (Frost et al. 1981; Berthelsen 1992). Thus, this metamorphism may have obliterated to some extent the differences in impedance between the deepest sedimentary units and the crystalline basement. However, compaction effects may also contribute to the vanishing of the impedance contrast between the deepest sedimentary sequences and the crystalline basement.

The block faulting of the basement indicates that the area has been subjected to crustal extension. According to Vejbæk (1997) such structures may be associated with the Carboniferous-Permian stretching which was active during the formation of the Norwegian-Danish Basin, although the RFH in general has undergone less extension than the areas of main regional subsidence.

The deep Palaeozoic sedimentary units have their largest thickness of more than 4 km about 20 km east of the Coffee Soil Fault. Even though the top basement boundary is heavily block faulted and has an undulating character, an overall thinning of the deep sedimentary units can be observed eastwards in the model. This thinning is most pronounced just west of the Horn Graben where the Palaeozoic strata have almost disappeared. Similarly, the Palaeozoic sedimentary cover is very thin or almost absent just east of the Central Graben. In the Per-1 well (cf. Fig. 1) Chalk-1 Unit has been indicated to rest directly on crystalline basement (Nielsen & Japsen 1990). We suggest that thinning of Palaeozoic sedimentary units in these two areas close to the two major graben structures is due to uplift and erosion of rift shoulders. The main phases of extension, graben formation and possible associated uplift of rift shoulders took place during the Triassic in the Horn Graben (Vejbæk 1990; Clausen & Korstgård 1993) and during the Jurassic in the Central Graben (Vejbæk 1992).

Conclusion

A model for pre-Zechstein Palaeozoic sedimentary units in the offshore Ringkøbing-Fyn High along the east-west trending MONA LISA line 3 has been presented. The model is based upon interpretation of both wide-angle and normal incidence deep seismic data. P-wave velocities modelled on the basis of the data from three wide-angle stations placed on the RFH show that the Palaeozoic units have velocities between 4.5 km/s and 5.1 km/s, clearly distinguishable from well defined velocities close to 6.0 km/s for the uppermost crystalline crust. Depths to the top of the crystalline basement have been modelled to be as large as 6–7 km and locally possibly up to 10 km. Details of the structure of the top basement boundary, which is constrained primarily by the normal incidence data, shows multiple block faults presumably formed as a consequence of Carboniferous-Permian crustal extension. A correlation between seismically interpreted thick and deep pre-Zechstein sedimentary units and negative free-air gravity anomalies is observed. Gravity observations north and south of MONA LISA line 3 indicate that significant thicknesses of pre-Zechstein strata are present in other parts of the offshore part of the Ringkøbing-Fyn system of basement highs.

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Dansk sammendrag

Tolkning af refrakterede og reflekterede observationer fra det kombinerede vidvinkel og nær-vertikal seismiske MONA LISA eksperiment i den sydøstlige del af Nordsøen viser tilstedeværelsen af tykke og dybe sedimentære lag i højderyggen mellem Central Graven og Horn Graven.

Der præsenteres en seismisk hastighedsmodel langs den øst-vest orienterede MONA LISA linie 3. I modellen observeres præ-Zechstein sedimentære lag, som lokalt er over 4 km i tykkelse. Lokalt når grænsen mellem de dybeste sedimentære lag og det krystalline basement ned til dybder på 7 km til 10 km. Overgangen fra de dybeste sedimenter til det krystalline grundfjeld er karakteriseret ved en række store blokforkastninger, der formodes at være relateret til karbon-permisk ekstension i skorpe-litosfæresystemet.

De dybe sedimenter, der er af præ-Zechstein alder, identificeres tydeligst v.h.a. refrakterede P-bølger, som viser hastigheder mellem 4.5 km/s og 5.1 km/s, hvilket er klart under 6.0 km/s, som er bestemt for det krystalline grundfjeld. I de nær-vertikale refleksionsseismiske data fra samme profil ses flere detaljer i interne og dybe strukturer i de sedimentære lag og i den øverste del af det krystalline grundfjeld.

På flankerne af Horn Graven og Central Graven observeres en tydelig udtynding af de palæozoiske lag. Det foreslås at udtyndingen i disse to områder skyldes opløft og erosion af rift-flankerne dannet i relation til riftningen i de to grav-systemer.

Der observeres en korrelation mellem gravimetriske friluftsanomalier og strukturer i toppen af det krystalline basement. De gravimetriske anomalier viser, at det er sandsynligt, at der findes lignende mægtigheder af palæozoiske sedimenter i områder af Ringkøbing-Fyn Højderyggen nord og syd for den analyserede linie, og sådanne palæozoiske lag kan således have betydelig udbredelse i den sydøstlige del af Nordsøen.

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