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Evaluation of the quality, thermal maturity and distribution of potential source rocks in the Danish part of the Norwegian–Danish Basin

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Norwegian–Danish Basin, source rocks, generation potential, maturation

Cover
Photomicrograph of alginite-rich organic matter from lacustrine sediments of the Frederikshavn Formation in the Terne-1 well (200–210 m depth; see also Fig. 39); the photograph is taken in fluorescence-inducing blue light. The sub-circular structure (*c.* 200 µm across) is an algal body that resembles the freshwater green alga *Botryococcus*.

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Contents

Abstract

Petersen, H.I., Nielsen, L.H., Bojesen-Koefoed, J.A., Mathiesen, A., Kristensen, L. & Dalhoff, F.* 2008: Evaluation of the quality, thermal maturity and distribution of potential source rocks in the Danish part of the Norwegian–Danish Basin. *Geological Survey of Denmark and Greenland Bulletin* 16, 66 pp.

The quality, thermal maturity and distribution of potential source rocks within the Palaeozoic–Mesozoic succession of the Danish part of the Norwegian–Danish Basin have been evaluated on the basis of screening data from over 4000 samples from the pre-Upper Cretaceous succession in 33 wells. The Lower Palaeozoic in the basin is overmature and the Upper Cretaceous – Cenozoic strata have no petroleum generation potential, but the Toarcian marine shales of the Lower Jurassic Fjerritslev Formation (F-III, F-IV members) and the uppermost Jurassic – lowermost Cretaceous shales of the Frederikshavn Formation may qualify as potential source rocks in parts of the basin. Neither of these potential source rocks has a basinwide distribution; the present occurrence of the Lower Jurassic shales was primarily determined by regional early Middle Jurassic uplift and erosion. The generation potential of these source rocks is highly variable. The F-III and F-IV members show significant lateral changes in generation capacity, the best-developed source rocks occurring in the basin centre. The combined F-III and F-IV members in the Haldager-1, Kvols-1 and Rønde-1 wells contain 'net source-rock' thicknesses (cumulative thickness of intervals with Hydrogen Index (HI) >200 mg HC/g TOC) of 40 m, 83 m, and 92 m, respectively, displaying average HI values of 294, 369 and 404 mg HC/g TOC. The Mors-1 well contains 123 m of 'net source rock' with an average HI of 221 mg HC/g TOC. Parts of the Frederikshavn Formation possess a petroleum generation potential in the Hyllebjerg-1, Skagen-2, Voldum-1 and Terne-1 wells, the latter well containing a *c.*160 m thick highly oil-prone interval with an average HI of 478 mg HC/g TOC and maximum HI values >500 mg HC/g TOC.

The source-rock evaluation suggests that a Mesozoic petroleum system is the most likely in the study area. Two primary plays are possible: (1) the Upper Triassic – lowermost Jurassic Gassum play, and (2) the Middle Jurassic Haldager Sand play. Potential trap structures are widely distributed in the basin, most commonly associated with the flanks of salt diapirs. The plays rely on charge from the Lower Jurassic (Toarcian) or uppermost Jurassic – lowermost Cretaceous shales. Both plays have been tested with negative results, however, and failure is typically attributed to insufficient maturation (burial depth) of the source rocks. This maturation question has been investigated by analysis of vitrinite reflectance data from the study area, corrected for post-Early Cretaceous uplift. A likely depth to the top of the oil window (vitrinite reflectance = 0.6%R_o) is *c.* 3050–3100 m based on regional coalification curves. The Frederikshavn Formation had not been buried to this depth prior to post-Early Cretaceous exhumation, and the potential source rocks of the formation are thermally immature in terms of hydrocarbon generation. The potential source rocks of the Fjerritslev Formation are generally immature to very early mature. Mature source rocks in the Danish part of the Norwegian–Danish Basin are thus dependent on local, deeper burial to reach the required thermal maturity for oil generation. Such potential kitchen areas with mature Fjerritslev Formation source rocks may occur in the central part of the study area (central–northern Jylland), and a few places offshore. These inferred petroleum kitchens are areally restricted, mainly associated with salt structures and local grabens (such as the Fjerritslev Trough and the Himmerland Graben).

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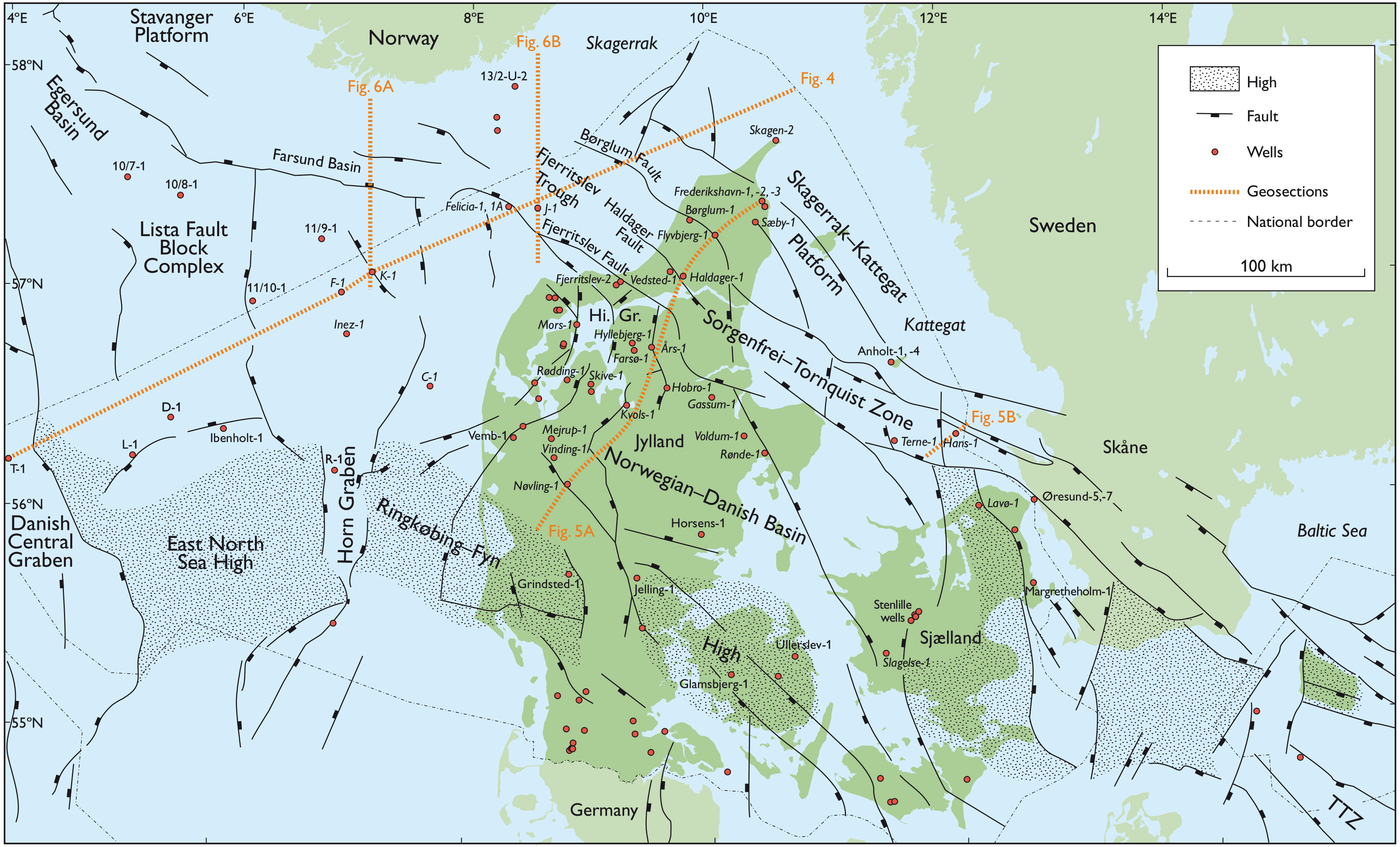


Fig. 1. Map showing well positions and the structural outline of the Norwegian–Danish Basin, the Sorgenfrei–Tornquist Zone, including the Fjerritslev Trough and the Himmerland Graben (**Hi. Gr.**), and the Skagerrak–Kattegat Platform. The major fault systems indicated are those active in the Mesozoic (cf. Figs 2, 3). Positions of geosections displayed in Figs 4–6 are also shown. Named wells are discussed in the text or used in log-panels; unnamed wells are indicated to illustrate the deep wells used in map compilation (e.g. Fig. 15). Assessment of the source-rock potential is based on data from wells indicated in italics. **TTZ**, Teisseyre–Tornquist Zone.

Introduction

This study focuses on an evaluation of source rocks in the Danish part of the Norwegian–Danish Basin, which is largely equivalent to the Danish Embayment and the Danish Subbasin of earlier workers (Figs 1, 2; Sorgenfrei & Buch 1964; Larsen 1966; Michelsen 1975, 1978, 1989a, b; Bertelsen 1978). The Danish part of the Norwegian–Danish Basin (referred to hereafter as 'the study area') covers onshore Denmark and Danish offshore territory extending as far west as the eastern margin of the Danish Central Graben in the North Sea. Several sub-basins occur in the area, including the Himmerland Graben and the Fjerritslev Trough (Fig. 2).

Since 1935, more than 60 deep wells have been drilled throughout the study area (see Fig. 2), yielding valuable information related to petroleum prospectivity (Fig. 1). Some of the wells were drilled for geothermal energy or gas storage, but the majority of the wells in the basin were hydrocarbon exploration wells, the main target being the Mesozoic succession (Sorgenfrei & Buch 1964; Nielsen & Japsen 1991). The Mesozoic petroleum system that relies on Lower Jurassic source rocks of the Fjerritslev Formation is considered to be the principal petroleum system in the Norwegian–Danish Basin. In the study area, the dominant play models have involved sandstones of the Upper Triassic – lowermost Jurassic Gassum Formation or the Middle Jurassic Haldager Sand and Bryne Formations charged from source rocks within the Lower Jurassic (Fjerritslev Formation) or the uppermost Jurassic – lowermost Cretaceous (Børglum, Frederikshavn, Tau and Mandal Formations). These plays have been tested by more than 30 wells placed on structures or stratigraphic pinch-outs. The results of wildcat drilling in the study area have so far been disappointing as only poor indications of hydrocarbons have been encountered in the wells. The primary source rocks, the F-III and F-IV members of the Fjerritslev Formation, have previously been determined to be immature to very early mature in the wells drilled. The wells have mainly been drilled on positive structures, but regional seismic data also support a relatively shallow burial depth for the Lower Jurassic source-rock intervals over much of the study area. Sufficient burial of the source rocks prior to Late Cretaceous – Palaeogene inversion events and Neogene exhumation may have occurred in localised depressions, however, such as in rim synclines developed adjacent to salt diapirs. The Mesozoic succession has also been tested in the Norwegian part of the basin and the border zone by *c.* 10 wells, also with poor results in terms of hydrocarbons. The Norwegian Farsund Basin (Fig. 1), immediately north of the study area, has recently been drilled, and the well encountered Jurassic sandstones and Lower Permian – Carboniferous rocks without indications of hydrocarbons. However, oil probably charged from Lower Jurassic (Fjerritslev Formation) and Upper Jurassic (Tau Formation) source rocks is under production from Middle–Upper Jurassic sandstones (Sandnes reservoir) in the Yme Field, situated in the Egersund Basin some 75–100 km west of the study area in the north-western part of the Norwegian–Danish Basin (Fig. 1; Husmo *et al.* 2003).

Aims of this study

The primary aim of this bulletin is to provide a comprehensive assessment of the quality, thermal maturity and distribution of potential source rocks within the Palaeozoic–Mesozoic succession of the central area of the Danish part of the Norwegian–Danish Basin (Fig. 2). Source-rock quality has been assessed by evaluation of screening data (total organic carbon (TOC) contents, S_2 pyrolysis yields, Hydrogen Index (HI) values) from more than 4000 samples from the pre-Upper Cretaceous succession in 33 wells (Fig. 1). T_{max} values and vitrinite reflectance (VR) data have been used to determine the thermal maturity of potential source rocks.

In order to assess the maturity of the various source-rock levels in the study area, an understanding of Neogene exhumation is essential. A previously published coalification curve that was corrected for post-Early Cretaceous exhumation on the basis of sonic velocity data suggested that the Lower Jurassic source-rock interval is immature to very early mature and the uppermost Jurassic – lowermost Cretaceous interval is immature in the Danish wells (Petersen *et al.* 2003a). In this study, new regional coalification (maturation) curves are presented based on a large number of VR measurements (a total of 560 VR values from 26 wells). The present-day depths of the samples have been corrected for (1) post-Early Cretaceous net-exhumation magnitudes derived from chalk velocities, and (2) post-Early Cretaceous net-exhumation magnitudes derived from re-evaluation of the shale sonic velocity data.

The secondary aim of this bulletin is to review the potential Mesozoic reservoirs in the study area, another critical element in a viable petroleum system.

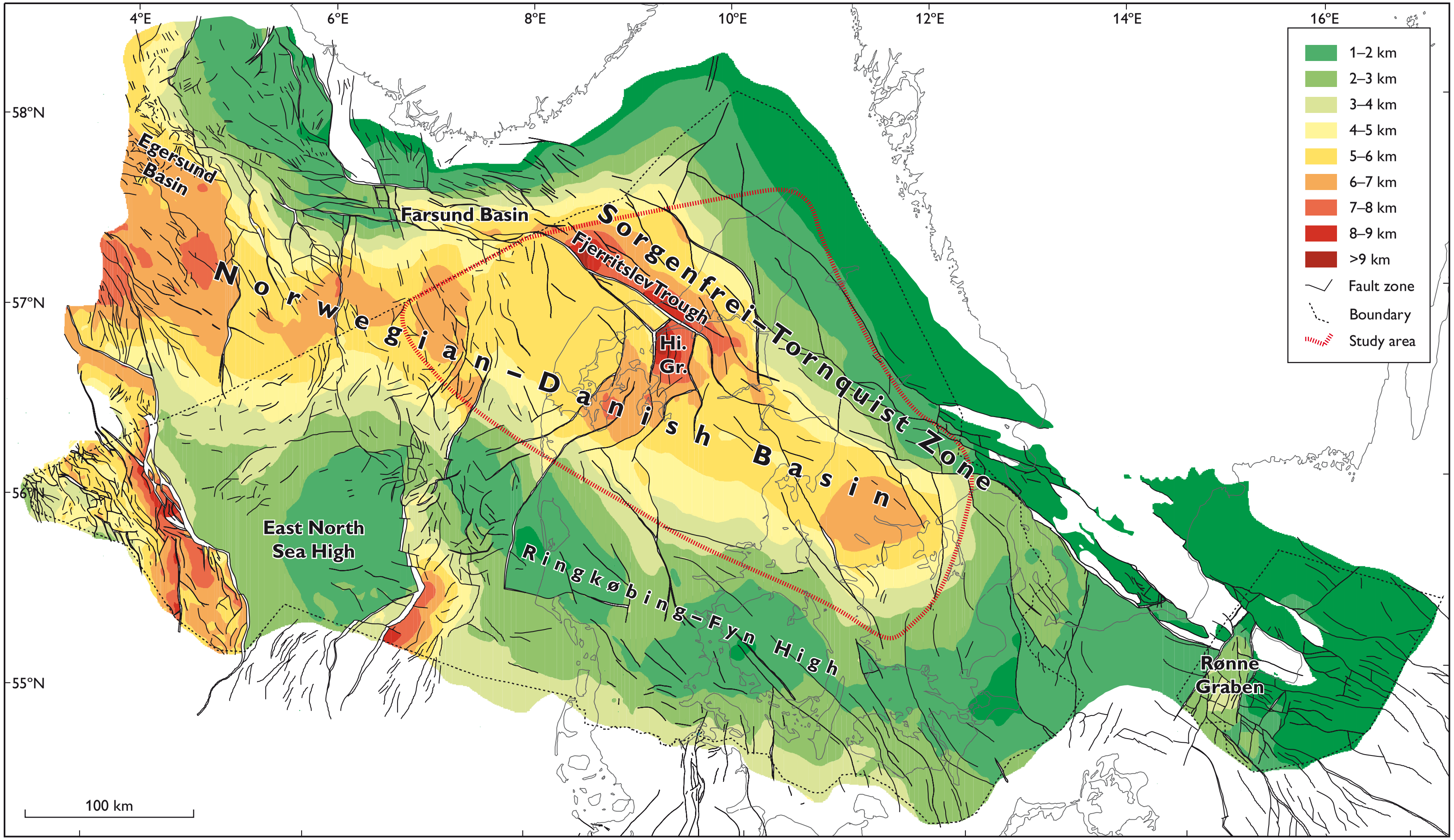


Fig. 2. Depth structure map of the top pre-Zechstein surface, the deepest surface that can be mapped by conventional seismic data in the Norwegian–Danish Basin; the extent of the study area covered by this bulletin is also shown. Note the large thicknesses in the Fjerritslev Trough and the Himmerland Graben (**Hi. Gr.**). Modified from Vejbæk (1997).

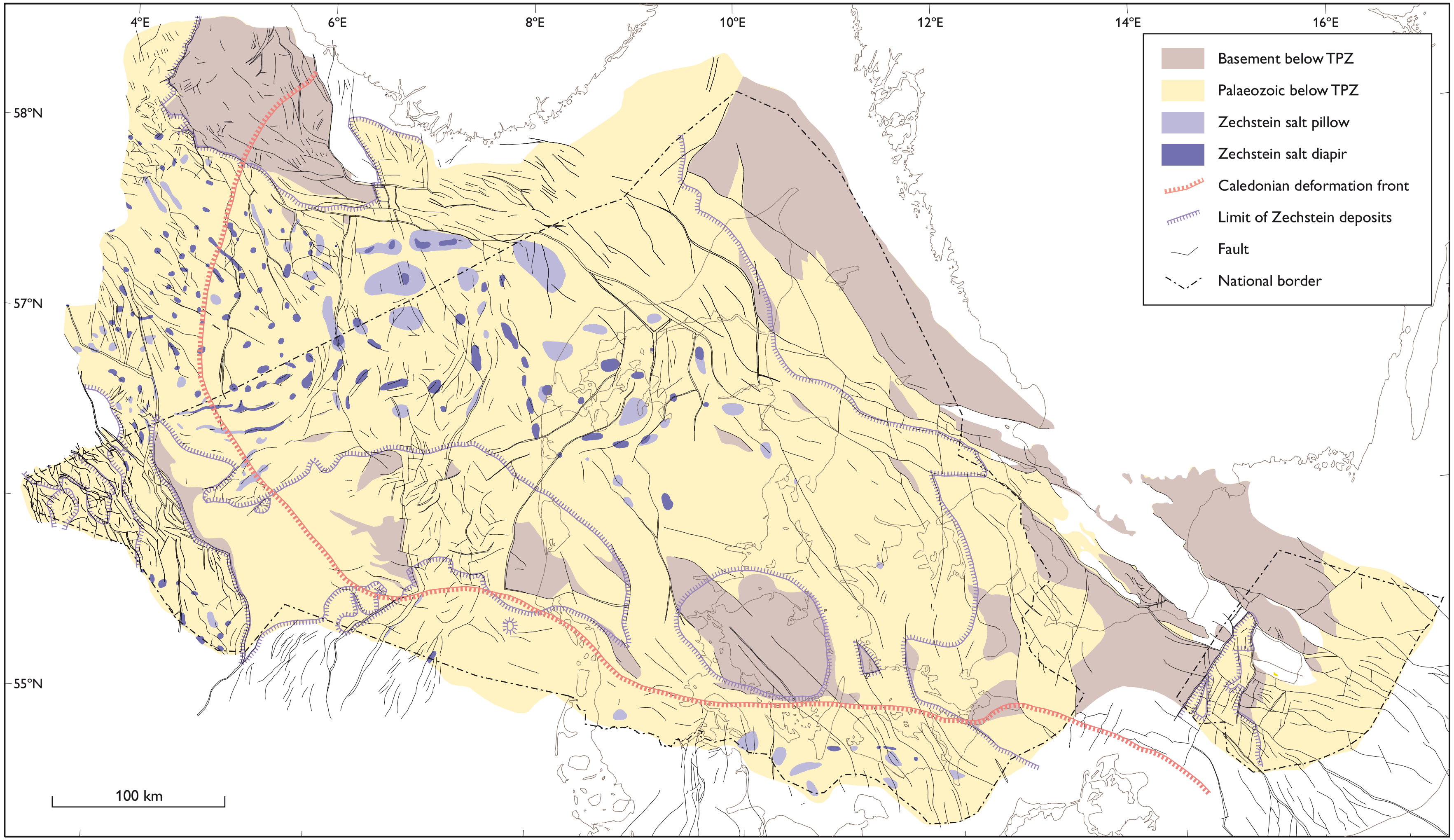
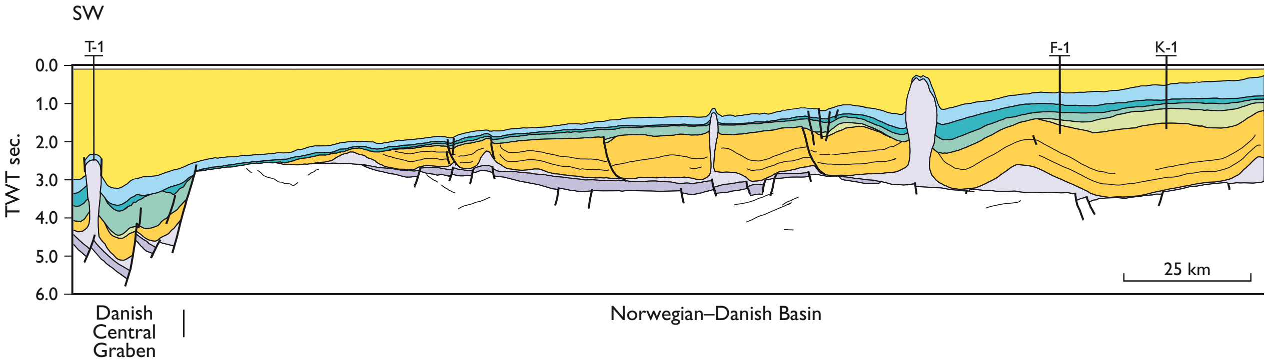


Fig. 3. Map showing the strata subcropping the top pre-Zechstein surface (and lateral correlative surface) and the distribution of known salt structures. The blue line indicates the limit of the Zechstein deposits (Vejbæk 1997). **TPZ**, Top pre-Zechstein.



Tectonic setting

The Danish part of the Norwegian–Danish Basin is a WNW–ESE-trending intracratonic basin, containing Permian–Cenozoic strata, that to the south is bounded by elevated Precambrian basement of the Ringkøbing–Fyn High and to the north-east and east by the Fennoscandian Border Zone. The Fennoscandian Border Zone consists of the Sorgenfrei–Tornquist Zone and the Skagerrak–Kattegat Platform that westwards passes into the Stavanger Platform north-east of the Egersund Basin; the zone marks the transition to the stable Precambrian Baltic Shield (Fig 1; Sorgenfrei & Buch 1964; Bergström 1984; EUGENO-S Working Group 1988; Michelsen & Nielsen 1991, 1993; Vejbæk 1997; Nielsen 2003). The Ringkøbing–Fyn High separates the Norwegian–Danish Basin from the North German Basin and was probably formed contemporaneously with the Norwegian–Danish Basin as an area of less crustal stretching (Figs 1–3). On the Skagerrak–Kattegat Platform, the Mesozoic section is relatively undisturbed; it onlaps tilted fault blocks comprising Precambrian crystalline basement, Lower Palaeozoic and Lower Permian strata and wedges out towards the north-east (Figs 4, 5A). The Sorgenfrei–Tornquist Zone is a highly block-faulted 30–50 km wide zone that runs SE–NW from the Rønne Graben in the Baltic Sea across southern Sweden through the Kattegat and northern Jylland to the Skagerrak, where it turns westwards across the Norwegian shelf (Figs 1–3, 5B). The zone includes the deep Fjerritslev Trough with a Zechstein–Mesozoic succession that locally is more than 9 km thick, and the shallower Farsund Basin where the Zechstein–Mesozoic section locally attains a thickness of slightly more than 6 km (Figs 2, 6).

The principal rifting phase of the Norwegian–Danish Basin and the Sorgenfrei–Tornquist Zone is defined by the occurrence of tilted fault blocks with basement rocks and Lower Palaeozoic strata unconformably overlain by Permian rocks (Figs 4–6; Liboriussen *et al.* 1987; Vejbæk 1989, 1997; Michelsen & Nielsen 1991, 1993; Jensen & Schmidt 1993; Christensen & Korstgård 1994; Vejbæk & Britze 1994). The crests of the fault blocks are deeply truncated and this top pre-Zechstein surface is the deepest regional surface that can be mapped on reflection seismic data in the Norwegian–Danish Basin and the Fennoscandian Border Zone (Fig. 3). The surface is relatively flat and smooth, indicating pronounced erosion prior to the Zechstein transgression. The unconformity is penetrated by wells that testify to the presence of Precambrian crystalline rocks on the Ringkøbing–Fyn High (Glamsbjerg-1, Grindsted-1, Ibenholt-1, Jelling-1) and the Skagerrak–Kattegat Platform (Frederikshavn-1) and Lower Palaeozoic sedimentary rocks in the Norwegian–Danish Basin and Fennoscandian Border Zone (Figs 1, 3; Nøvling-1, Rønde-1, Slagelse-1, Terne-1; Sorgenfrei & Buch 1964; Poulsen 1969, 1974; Larsen 1971, 1972; Christensen 1971, 1973; Nielsen & Japsen 1991; Michelsen & Nielsen 1991, 1993). The shallow IKU/Sintef borehole 13/2-U-2 encountered Silurian strata subcropping the Quaternary north-east of the Farsund Basin (Fig. 1).

The tilted fault-block crests are deeply truncated by the mid-Permian unconformity showing that regional post-rift thermal subsidence was somewhat delayed (Vejbæk 1997). The unconformity that defines the base of the post-rift sequence is overlain by a relatively complete succession of Zechstein salts and carbonates, Triassic clastics, carbonates and salts, Jurassic – Lower Cretaceous clastics, Upper Cretaceous chalks and Cenozoic clastics that attain a thickness of 5–6.5 km along the basin axis. A similar thickness of the post-rift succession is found in the Farsund Basin, where the succession is more than 3 sec. (TWT) thick in

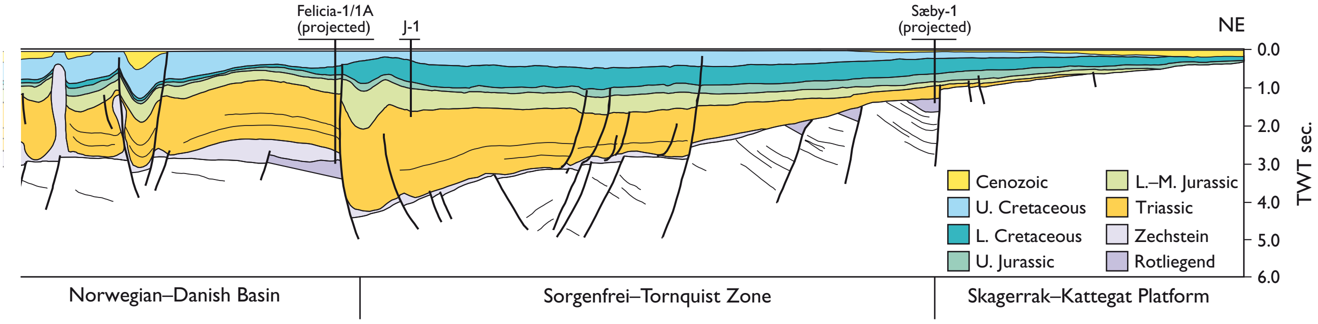


Fig. 4. Regional geosection from the Central Graben in the south-west to the Skagerrak–Kattegat Platform in the north-east showing pinch-out of the Mesozoic strata on the Skagerrak–Kattegat Platform. For location of section, see Fig. 1. **TWT**, Two-Way Travel Time.

places, corresponding to slightly more than 6 km (Jensen & Schmidt 1993; Vejbæk & Britze 1994), whereas the succession is more than 9 km thick locally in the Fjerritslev Trough and the Himmerland Graben (Fig. 2). Isochore maps of the Triassic and Jurassic – Lower Cretaceous successions show a relatively uniform regional thickness over most of the basin, except for areas influenced by local halokinetic movements, indicating relatively uniform thermal subsidence (Vejbæk 1989, 1997; Britze & Japsen 1991; Japsen & Langtofte 1991). Although the thick Upper Permian – Triassic succession indicates rapid subsidence that exceeds rates normally associated with post-rift thermal contraction (Fig. 7), a prolonged or new rifting phase is precluded by the general lack of pronounced extensional faulting in the Mesozoic succession; phase transformations in the deep crust have been proposed to explain the rapid, early post-rift subsidence (Vejbæk 1989, 1997). Deposition and preservation of great thicknesses of Mesozoic sediments in the Himmerland Graben and the Fjerritslev Trough were facilitated by transtensional strike-slip movements in the Sorgenfrei–Tornquist Zone or large-scale salt movements (Pegrum 1984; Vejbæk 1989; Christensen & Korstgård 1994; Mogensen 1994, 1996). Growth of salt structures influenced Mesozoic deposition locally.

The Ringkøbing–Fyn High was uplifted significantly in early Middle Jurassic times and the Norwegian–Danish Basin became tilted to the north-east (Michelsen 1978; Koch 1983; Andsbjerg *et al.* 2001; Nielsen 2003). The uplift and tilting caused progressively deeper erosive truncation of the Lower Jurassic and Triassic across the basin towards the Ringkøbing–Fyn High, where erosion removed the entire Lower Jurassic and much of the Triassic on the most elevated parts of the high (Fig. 8). In contrast, subsidence continued during Middle Jurassic times in the Sorgenfrei–Tornquist Zone, as shown by well sections in the Øresund region (Øresund-5, -7), in the Kattegat area (Terne-1, Anholt-4), and in the Fjerritslev Trough (Børglum-1, Fjerritslev-2, Flyvbjerg-1, J-1, Haldager-1, Vedsted-1), but at a much lower rate than in Triassic – Early Jurassic times (Fig. 7). Danish well sections on the Skagerrak –Kattegat Platform (Frederikshavn-1, -2, -3, Skagen-2, Sæby-1) indicate that only limited erosion occurred north of the Fjerritslev Trough.

Regional subsidence gradually resumed during late Middle – Late Jurassic times and tectonic tranquillity generally prevailed, except for local salt movements, until inversion occurred in the Sorgenfrei–Tornquist Zone. A Late Cretaceous – Palaeogene age is generally accepted for the inversion, which is interpreted to have been caused by compression related to a change in the regional stress field from extensional to compressional, linked to Alpine deformation and opening of the North Atlantic (Liboriussen *et al.* 1987; Ziegler 1990; Michelsen & Nielsen 1991, 1993; Mogensen & Korstgård 2003). The inversion may have occurred in several phases, however, and it is assumed to have begun in Turonian times or earlier in the south-east, with 1.5–3 km of uplift in the Skåne–Bornholm area, and propagated north-westwards with decreasing intensity of deformation (Berthelsen 1992; Mogensen & Jensen 1994; Michelsen 1997; Petersen *et al.* 2003a; Japsen *et al.* 2007). After cessation of the inversion, a new quiescent tectonic phase began with regional subsidence of the greater North Sea Basin. Contemporaneously with the regional down-warping of southern Scandinavia, significant uplift and erosion began to influence parts of the Norwegian–Danish Basin and the Ringkøbing–Fyn High in Neogene times (Japsen 1993; Jensen & Schmidt 1993; Japsen *et al.* 2002a, b, 2007).

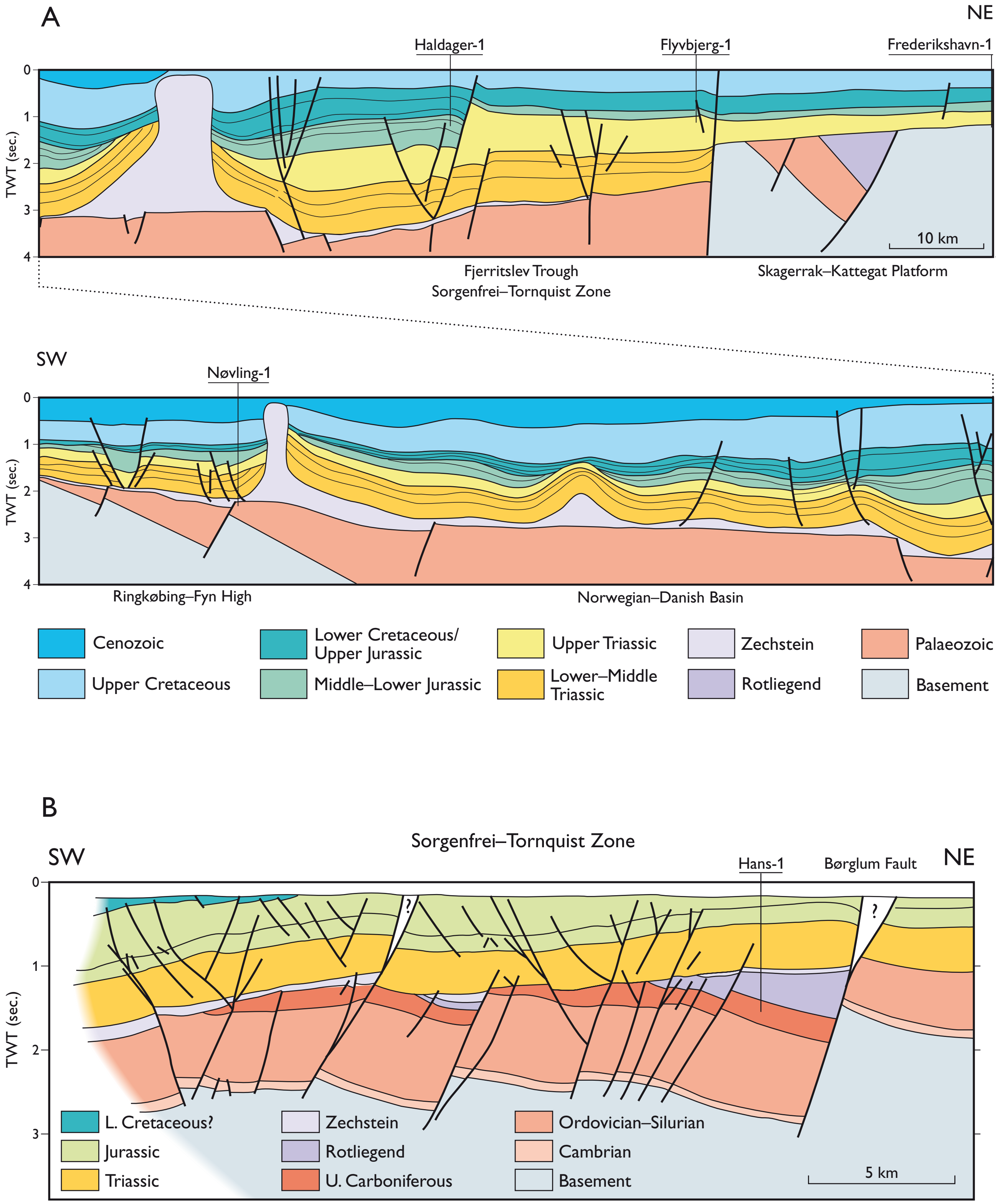


Fig. 5. Geosections modified from Michelsen & Nielsen (1991); for locations, see Fig. 1. **A**: Regional geosection across the Danish part of the Norwegian–Danish Basin showing thickening of the Mesozoic section in the Fjerritslev Trough / Sorgenfrei–Tornquist Zone. **B**: Geosection from the Kattegat through the Hans-1 well; note Palaeozoic fault blocks.

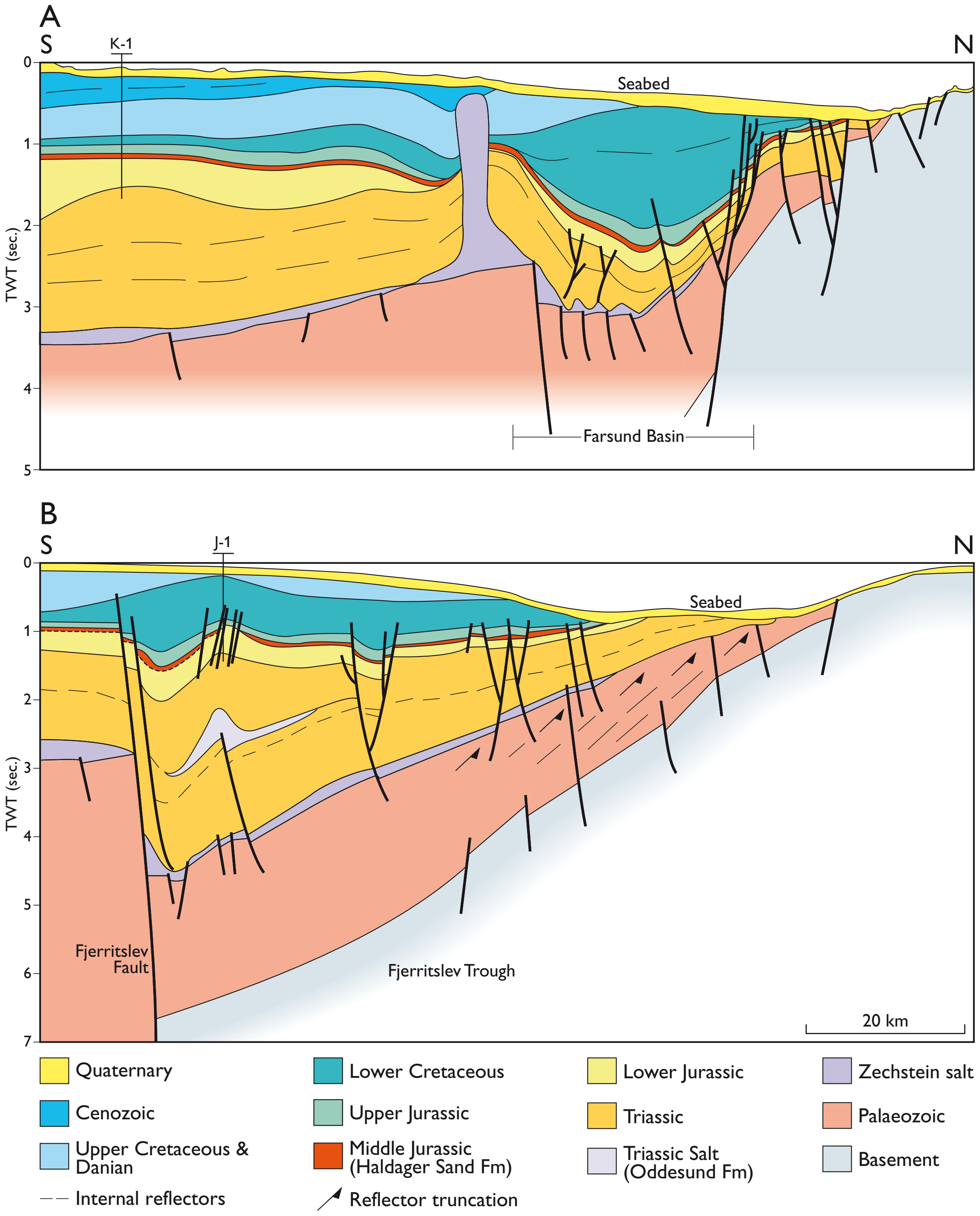


Fig. 6. Geosections modified from Jensen & Schmidt (1993); for locations, see Fig 1. **A**: Geosection from the Norwegian–Danish Basin across the Fjerritslev Fault and the Farsund Basin. The Middle Jurassic Haldager Sand reservoir overlying the Lower Jurassic potential source rocks is marked in red. Note Palaeozoic fault blocks overlain by Zechstein salt. **B**: Geosection from the Fjerritslev Trough.

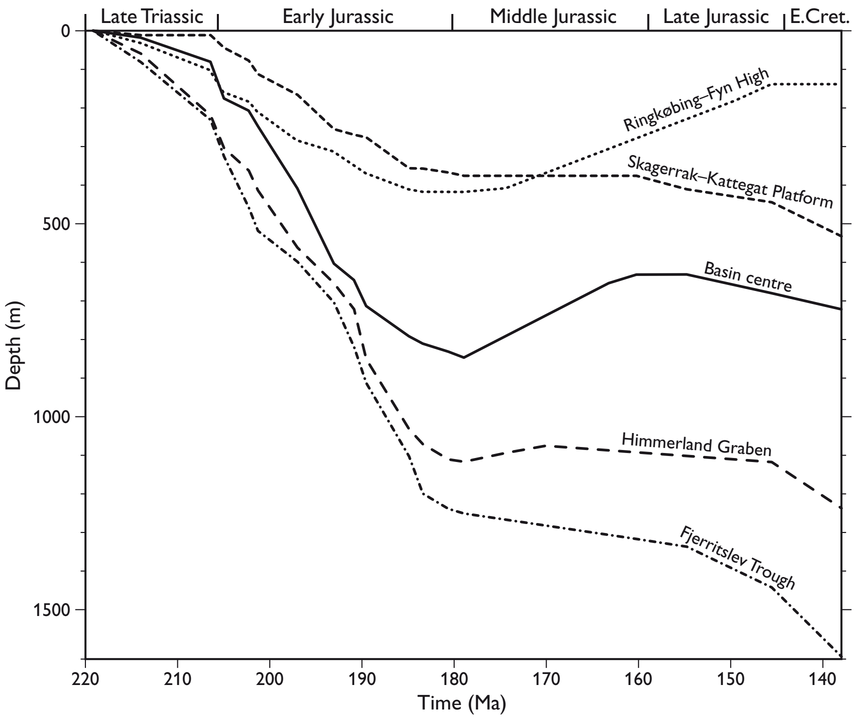


Fig. 7. Subsidence curves for the Late Triassic – Early Cretaceous constructed for different structural elements/sub-basins within the Norwegian–Danish Basin, Skagerrak – Kattegat Platform and Ringkøbing–Fyn High based on a sequence stratigraphic break-down (Nielsen 2003).

Depositional development and stratigraphy

A review of the Permian–Cenozoic depositional evolution of the basin is presented here to provide a framework for discussion of potential components of a petroleum system in the Danish portion of the Norwegian–Danish Basin. For detailed, comprehensive accounts of the basin evolution and stratigraphy, the reader is referred to Michelsen *et al.* (2003) and Nielsen (2003).

Zechstein evaporites

Deposition of the post-rift succession was initiated in Late Permian times with the accumulation of thick Zechstein evaporites in most of the Norwegian–Danish Basin. Marginal facies were developed along parts of the Ringkøbing–Fyn High in Late Permian times, and as the Lower Triassic Bunter Shale Formation seems to rest on deeply weathered basement in the Grindsted-1 well, it is likely that the high formed a barrier between the Southern and Northern Zechstein basins (Ziegler 1982; Stemmerik *et al.* 1987; Vejbæk 1997). Later mobilisation of Zechstein salt led to the formation of salt structures such as pillows and diapirs (Fig. 3), and the continued growth of salt structures influenced Mesozoic deposition in places. Towards the east, the evaporites are replaced by thin clastic Zechstein deposits as shown by the Terne-1 and Hans-1 wells in the Sorgenfrei–Tornquist Zone (Michelsen & Nielsen 1991, 1993). Farther north-west in the Sorgenfrei–Tornquist Zone, however, evaporites are present in the Fjerritslev Trough and the Farsund Basin (e.g. Liboriussen *et al.* 1987; Jensen & Schmidt 1993; Christensen & Korstgård 1994; Vejbæk 1997).

Early–Middle Triassic clastic deposition

In Early Triassic times, the depositional environment changed to more continental conditions. Similarity in depositional facies in the North German and Norwegian–Danish Basins indicates that the two basins were connected, at least periodically (Bertelsen 1978; Michelsen & Clausen 2002). The facies encountered in the Jelling-1 and Grindsted-1 wells located on the northern flank of the Ringkøbing–Fyn High belong to the Bunter Shale, Bunter Sandstone, Ørslev, Falster and Tønder Formations; these formations may be traced farther northwards to the Mors-1

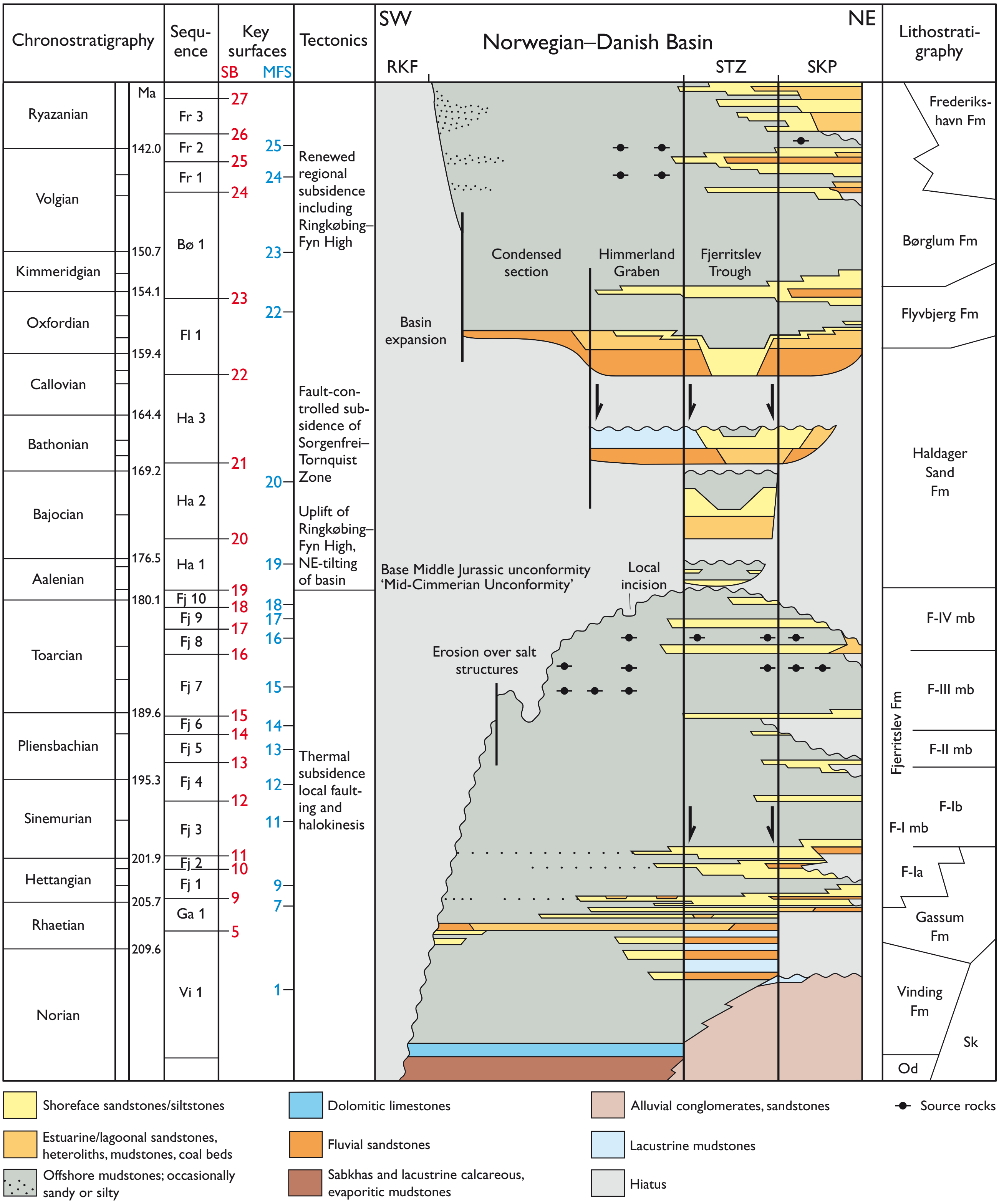


Fig. 8. Time-stratigraphic scheme of the Upper Triassic – Lower Cretaceous trending SW–NE across the Norwegian–Danish Basin. Sequence stratigraphic key surfaces are included, numbered sequence boundaries are shown in red (**SB**) and maximum flooding surfaces shown in blue (**MFS**). The SBs bound the named sequences (e.g. Vi 1, Ga 1). The main tectonic events are indicated. Note the significant base Middle Jurassic unconformity that cuts deep into older strata to the south-west and is onlapped as the area of subsidence expanded during Late Jurassic times. **Od**, Oddesund Formation; **RKF**, Ringkøbing–Fyn High; **Sk**, Skagerrak Formation; **SKP**, Skagerrak–Kattegat Platform; **STZ**, Sorgenfrei–Tornquist Zone. Modified from Nielsen (2003); time-scale from Gradstein *et al.* (1994).

well, in which the succession reflects a transition to the contemporaneous Skagerrak Formation that dominates along the northern and eastern basin margin (Bertelsen 1980; Nielsen & Japsen 1991). The Bunter Shale and Bunter Sandstone Formations are present in Felicia-1A, whereas the Ørslev, Falster and Tønder Formations are replaced by the Skagerrak Formation. The Bunter Sandstone Formation may also be present in the Terne-1 well where the lower 155 m of the Triassic succession consists mainly of fine-grained, well-sorted sandstones. The Bunter Sandstone Formation mainly consists of red-brown and yellow-brown, medium- to fine-grained, well-sorted sandstones with intraformational claystone clasts and thin mudstone beds, largely recording deposition in ephemeral, braided fluvial channels in an arid desert environment (Bertelsen 1980; Pedersen & Andersen 1980). Eolian dune sand, and mud deposited in ephemeral lakes, may constitute minor proportions of the formation. Up-section and towards the northern and north-eastern basin margin, the Bunter Sandstone Formation passes into the Skagerrak Formation. On the Skagerrak–Kattegat Platform, Lower –Middle Triassic strata are all referred to the Skagerrak Formation, which here seems to include large parts of the Upper Triassic as well (Frederikshavn-1, -2, -3, Sæby-1; Nielsen & Japsen 1991; Figs 8, 9). The formation consists of a heterogenous succession of interbedded conglomerates, sandstones, siltstones and claystones that were mainly deposited as alluvial fans along the basin margins.

Late Triassic clastic and evaporitic deposition and marine flooding

In Late Triassic times, the arid or semi-arid climate continued and deposition of variegated red-brown or brown, calcareous, anhydritic and pyritic mudstones and siltstones with thin beds of dolomitic limestone and marl commenced in sabkhas and ephemeral lakes. In the central, deep parts of the basin, more permanent lakes were established. The deposits are included in the Carnian – Lower Norian Oddesund Formation, which passes into the Skagerrak Formation towards the basin margins to the north and north-east (Figs 8, 9; Bertelsen 1980). In places, the Oddesund Formation includes two halite units up to 90 m thick, which in some areas have contributed to the formation of salt domes together with the Zechstein salts (Liboriussen *et al.* 1987; Jensen & Schmidt 1993; Christensen & Korstgård 1994).

A gradual change to more humid conditions took place in Late Triassic times, associated with an Early Norian marine transgression that probably came from the south and resulted in the formation of a large epicontinental sea. The transgression led to deposition of oolitic limestones succeeded by marlstones and fossiliferous claystones of the Vinding Formation, which is typically 40–100 m thick over most of the basin (Figs 8–10; Bertelsen 1978, 1980; Nielsen 2003). At its maximum extent in Late Norian times, the shallow sea covered most of the central basin and the Ringkøbing–Fyn High, whereas deposition of fluvial arkosic sands and lacustrine muds of the Skagerrak Formation continued in the Sorgenfrei–Tornquist Zone and on the Skagerrak–Kattegat Platform. Maximum transgression was followed by phased regression, and shoreface and fluvial sands of the lower Gassum Formation were deposited in stepwise, more basinward positions; the sands are interbedded with clays of the upper Vinding Formation in the basin centre. Deposition of fluvial sand and lacustrine mud of the Skagerrak Formation continued in the Fjerritslev Trough (Figs 8, 10). Regression culminated in the early Rhaetian with the formation of an extensive, fluvially incised sequence boundary (SB 5 of Nielsen 2003; Figs 8, 10). The following, widespread marine flooding was initiated with deposition of fluvial–estuarine sediments, up to 30 m thick in the basin centre, above the sequence boundary. The transgression was punctuated by two short-term, forced regressions that led to deposition of widespread shoreface sand sheets encased in offshore mud (Hamberg & Nielsen 2000; Nielsen 2003). The transgression reached its maximum in the latest Rhaetian, when the entire study area and the Ringkøbing–Fyn High were covered by the sea, and marine mudstones were deposited widely (MFS 7; Figs 8, 10–11).

Hettangian – Early Pliensbachian transgression and basin expansion

During latest Rhaetian times, the climate changed to the subtropical to warm-temperate and humid conditions that characterised the Jurassic period, when large quantities of clay were supplied to the basin due to weathering of Palaeozoic shales and granitic basement of the Baltic Shield. The Jurassic transgression was interrupted by two phases of coastal progradation that caused deposition of two thin, regressive, shoreface sand sheets, which constitute the uppermost part of the Gassum Formation over much of the study area. The regression culminated in coastal progradation far into the basin accompanied by fluvial erosion and incision in the Himmerland Graben, the Fjerritslev Trough and the Skagerrak–Kattegat Platform (SB 9; Figs 10–11). Subsequently, the regional transgression continued (TS 9; early Hettangian Planorbis Zone), so that fully marine mud-

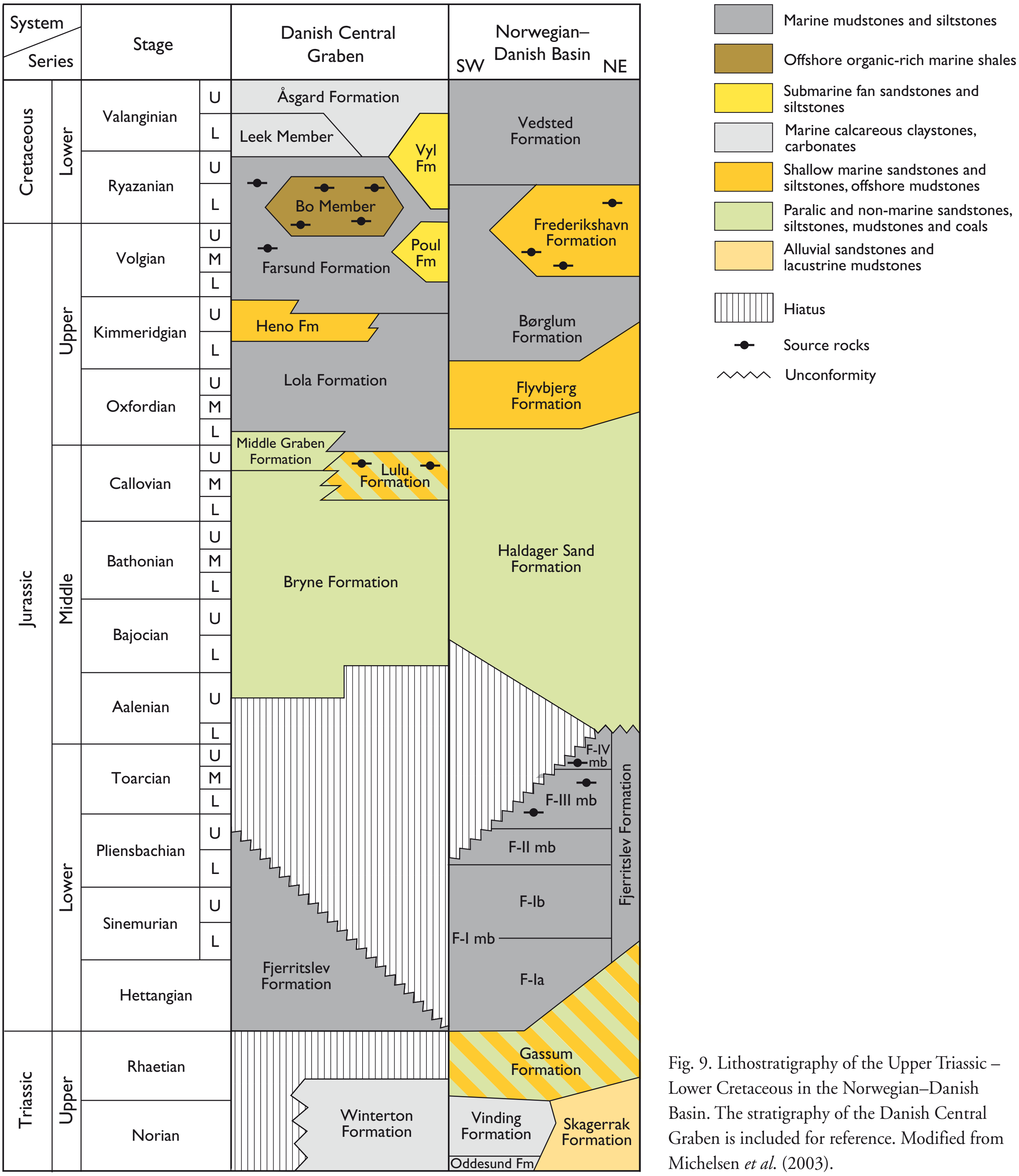


Fig. 9. Lithostratigraphy of the Upper Triassic – Lower Cretaceous in the Norwegian–Danish Basin. The stratigraphy of the Danish Central Graben is included for reference. Modified from Michelsen *et al.* (2003).

stones belonging to the F-Ia unit of the F-I member of the Fjerritslev Formation overlie the sandy Gassum Formation over most of the study area (Figs 8–14). The mudstones have a high content of land-derived organic matter. The transgression peaked in the early and late Hettangian (MFS 9, 10), interrupted by a short-term regression in the middle Hettangian (SB 10; Figs 8, 10–12). Deposition of transgressive paralic deposits along the basin margin was interrupted briefly by a fall in sea level soon after the Hettangian–Sinemurian boundary. This resulted in fluvial

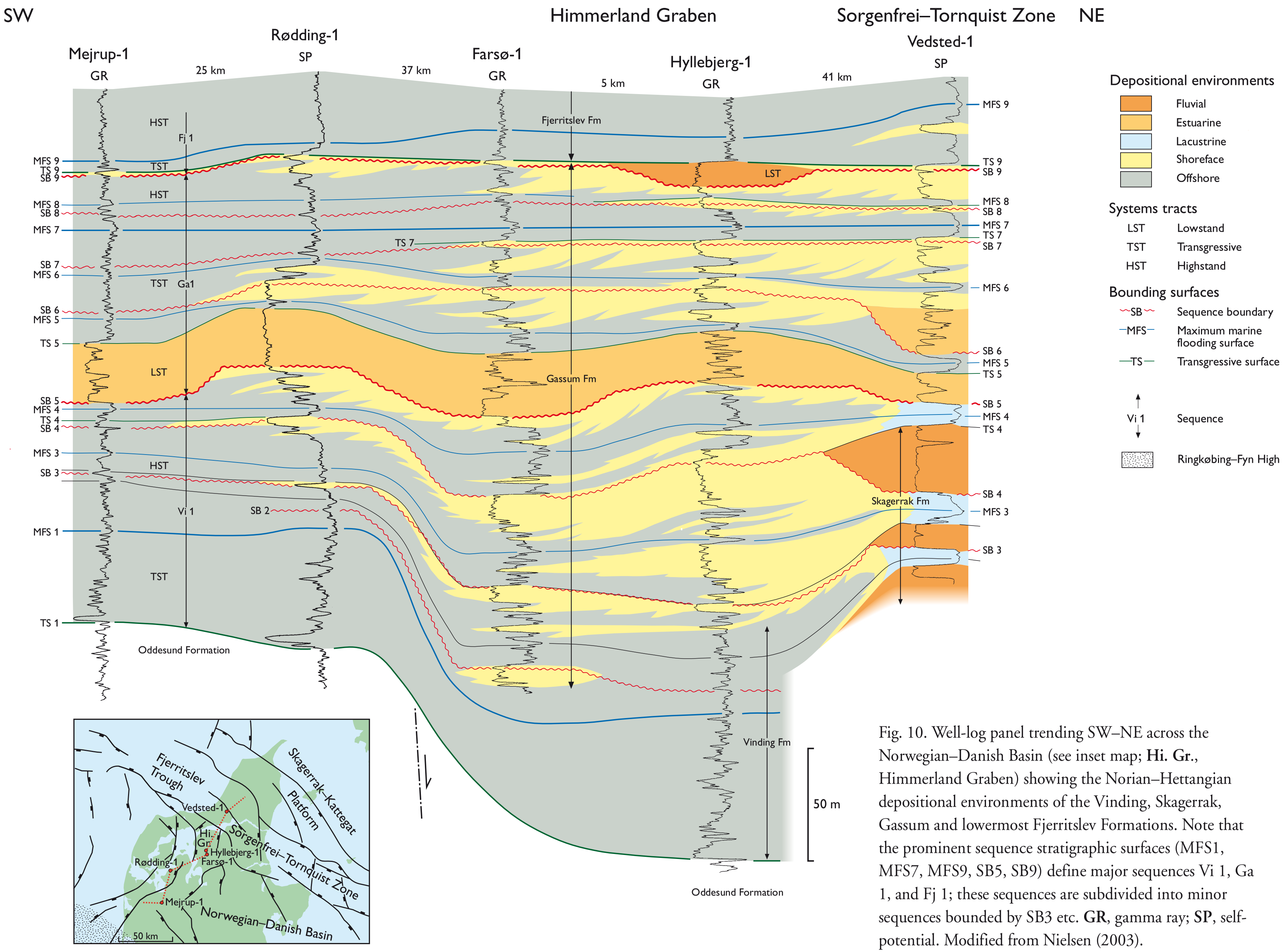


Fig. 10. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Norian–Hettangian depositional environments of the Vinding, Skagerrak, Gassum and lowermost Fjerritslev Formations. Note that the prominent sequence stratigraphic surfaces (MFS1, MFS7, MFS9, SB5, SB9) define major sequences Vi 1, Ga 1, and Fj 1; these sequences are subdivided into minor sequences bounded by SB3 etc. **GR**, gamma ray; **SP**, self-potential. Modified from Nielsen (2003).

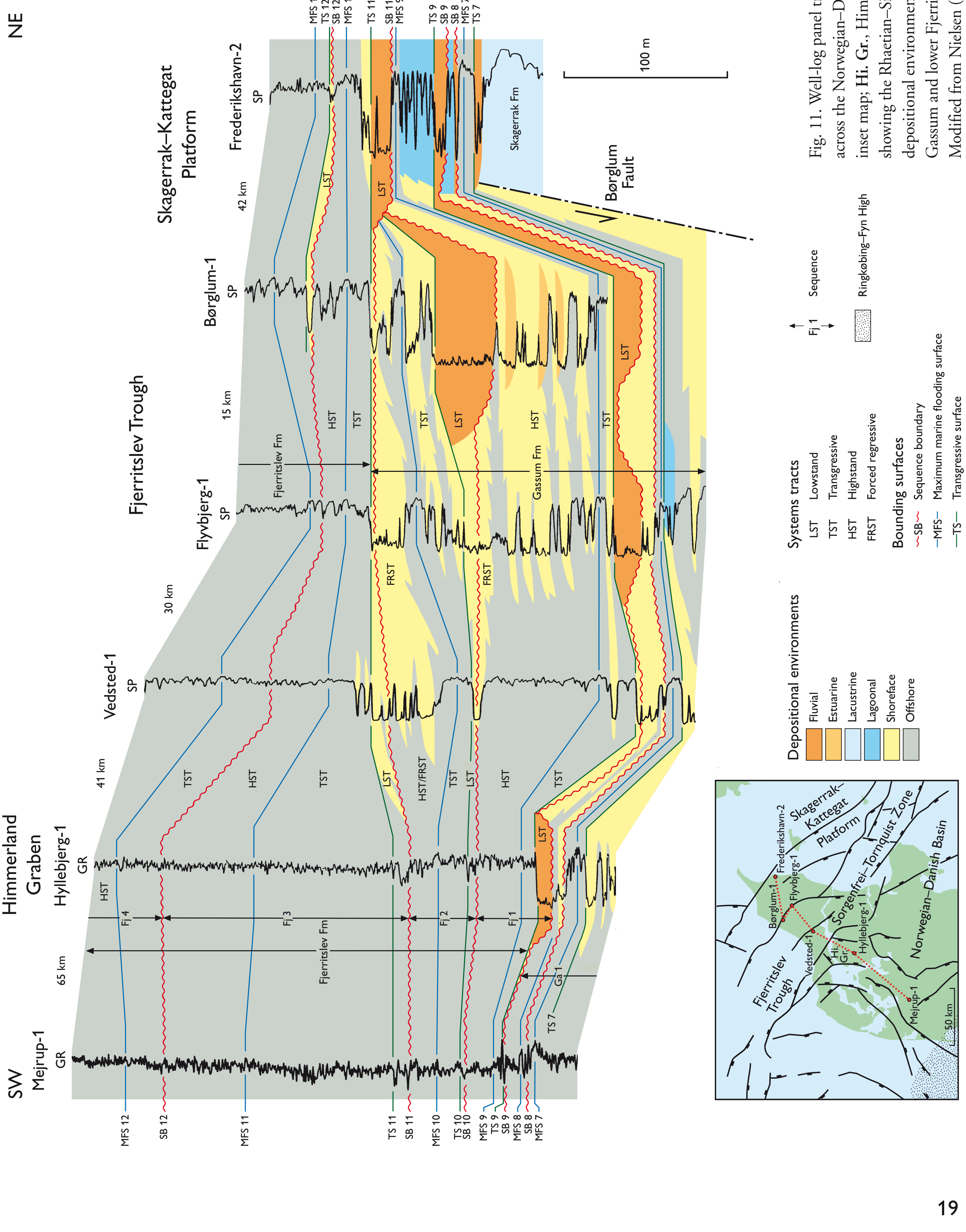


Fig. 11. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Rhaetian–Sinemurian depositional environments of the upper Gassum and lower Fjerritslev Formations. Modified from Nielsen (2003).

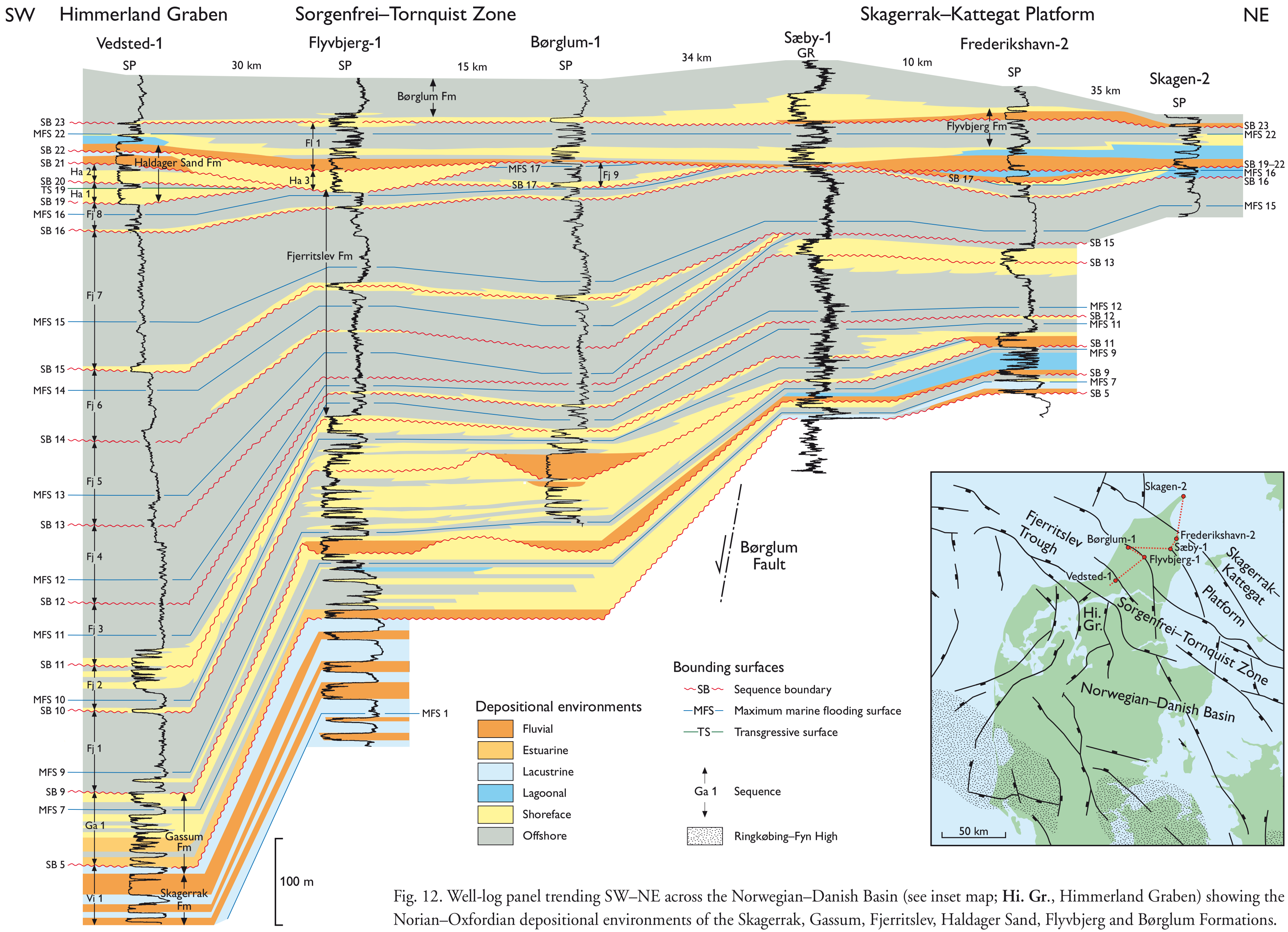


Fig. 12. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Norian–Oxfordian depositional environments of the Skagerrak, Gassum, Fjerritslev, Haldager Sand, Flyvbjerg and Børglum Formations. Note the pronounced erosional truncation at the amalgamated sequence boundary, SB 19–22. Modified from Nielsen (2003).

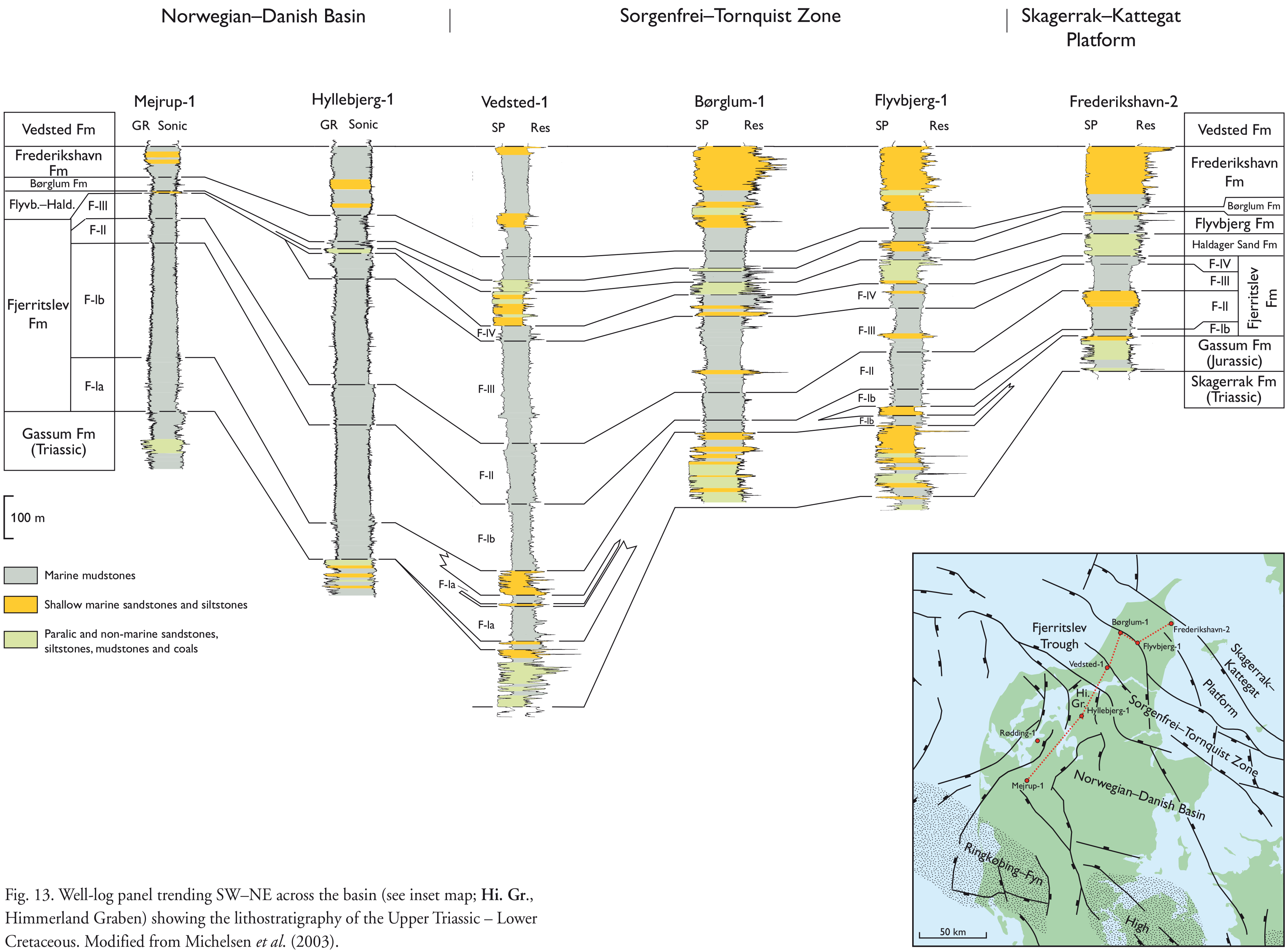


Fig. 13. Well-log panel trending SW–NE across the basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the lithostratigraphy of the Upper Triassic – Lower Cretaceous. Modified from Michelsen *et al.* (2003).

incision on the Skagerrak–Kattegat Platform, while regressive shoreface sand was deposited in the Fjerritslev Trough (SB 11; Figs 8, 11–12). Farther basinwards, heteroliths and silty mudstones were deposited above the conformable part of the sequence boundary.

A rapid sea-level rise followed in the earliest Sinemurian (upper part of the Bucklandi Zone), and transgressive marine muds of the F-Ib unit of the F-I member of the Fjerritslev Formation finally overstepped fluvial and marine sands of the Gassum Formation in the Sorgenfrei–Tornquist Zone and on the Skagerrak–Kattegat Platform (Figs 8, 9, 13, 14). The early Sinemurian transgression led to deposition of up to 150 m of uniform mudstones in the basin, showing a marked thinning towards the northern and north-eastern basin margin (Sequence Fj 3 in Figs 8, 11, 12). Following a minor sea-level fall in the Late Sinemurian, the overall Early Jurassic sea-level rise continued and reached a maximum in the latest Sinemurian (Fig. 14). In the centre of the basin, the diversity and abundance of the ostracod fauna decreased and infaunal bivalves and some of the epifaunal bivalves disappeared due to reduced oxygen conditions (Pedersen 1986; Michelsen 1989a).

A gradual decrease in the rate of sea-level rise in the Early Pliensbachian Jamesoni Zone caused a distinct basinward progradation of shoreface clinoform sandstones on the Skagerrak–Kattegat Platform. The regression culminated in the middle Early Pliensbachian (early Ibex Zone) and deposition changed from fine-grained mud (F-Ib unit, F-I member) to silty and sandy heteroliths (F-IIa unit, F-II member, SB 13; Figs 8, 9, 12–14; Michelsen 1989a; Nielsen 2003). When the sea level started to rise again, deposition of fine-grained mud resumed in the basin (lower part of F-IIb unit, F-II member, Fjerritslev Formation), while backstepping parasequences of marine sand were succeeded by transgressive mud on the Skagerrak–Kattegat Platform. Peak transgression was reached in the late Early Pliensbachian Davoei Zone. Thereafter, the rate of sea-level rise decreased and a coarsening-upward succession of mud and fine-grained heteroliths was deposited in the study area (middle part of F-IIb unit, F-II member).

Late Pliensbachian – Early Aalenian sea-level fluctuations

Significant erosion took place on the Skagerrak–Kattegat Platform during a sea-level fall in the early Late Pliensbachian Margaritatus Zone (SB 14; Figs 8, 12). Basinwards, deposition changed to silty and sandy mud and fine-grained sand, showing pronounced thinning over some salt structures possibly reflecting shallow-water depths (upper part of F-IIb and F-IIc beds, F-II member; Michelsen 1989a, b). The ensuing sea-level rise reached a peak in the late Late Pliensbachian (early Spinatum Zone). Marine silty mud accumulated in the basin, while muddy marine sand with bivalves was deposited in the Fjerritslev Trough and presumably also in the Farsund Basin (lower part of the F-III member, Fjerritslev Formation; Figs 8, 9, 13). Strata from this period are absent on the Skagerrak–Kattegat Platform due to bypass or later erosion (Fig. 8).

A subsequent sea-level fall caused the formation of a widespread marine regressive surface of erosion and deposition of 5–10 m of lowstand shoreface sandstones in the central parts of the Fjerritslev Trough (SB 15; Figs 8, 12); Lower Pliensbachian strata were eroded on the Skagerrak–Kattegat Platform.

The subsequent sea-level rise caused marine flooding over the entire study area, and the transgression reached its maximum in the Early Toarcian Falciferum Zone (MFS 15; Figs 8, 12, 14). Due to oxygen-poor conditions, the ostracod fauna disappeared and an increasing amount of algal-derived marine organic matter was preserved, resulting in the accumulation of organic-rich, oil-prone mudstones in parts of the basin (F-III and F-IV members, see below; Figs 8, 9, 13). During the remainder of the Early Jurassic and in the Early Aalenian Opalinum Zone (early Middle Jurassic), a succession of up to 150 m of marine mudstones was deposited in the Sorgenfrei–Tornquist Zone (F-III and F-IV members, Fjerritslev Formation; Figs 8, 9, 12–14). Interbedded with the mudstones are three shoreface sandstones, 5–15 m thick, overlying regressive marine erosion surfaces. These sandstones were deposited during sea-level falls and could act as carrier beds for any petroleum generated and expelled from thermally mature Toarcian source rocks.

Late Early – Middle Jurassic uplift and erosion

The Ringkøbing–Fyn High and most of the Norwegian–Danish Basin were uplifted in late Early Jurassic – early Middle Jurassic times, and the Triassic – Lower Jurassic successions were eroded on the highest parts of the Ringkøbing–Fyn High (Figs 8, 14, 15). The Lower Jurassic succession, including the potential source-rock intervals of the Fjerritslev Formation, was deeply eroded in the uplifted area north of the high. Outside the study area, towards the north-west, Norwegian wells (10/7-1, 10/8-1, 11/9-1, 11/10-1; Fig. 1) confirm the deep regional erosion of the Lower Jurassic succession, although the large hiatuses recorded in these wells may not be representative

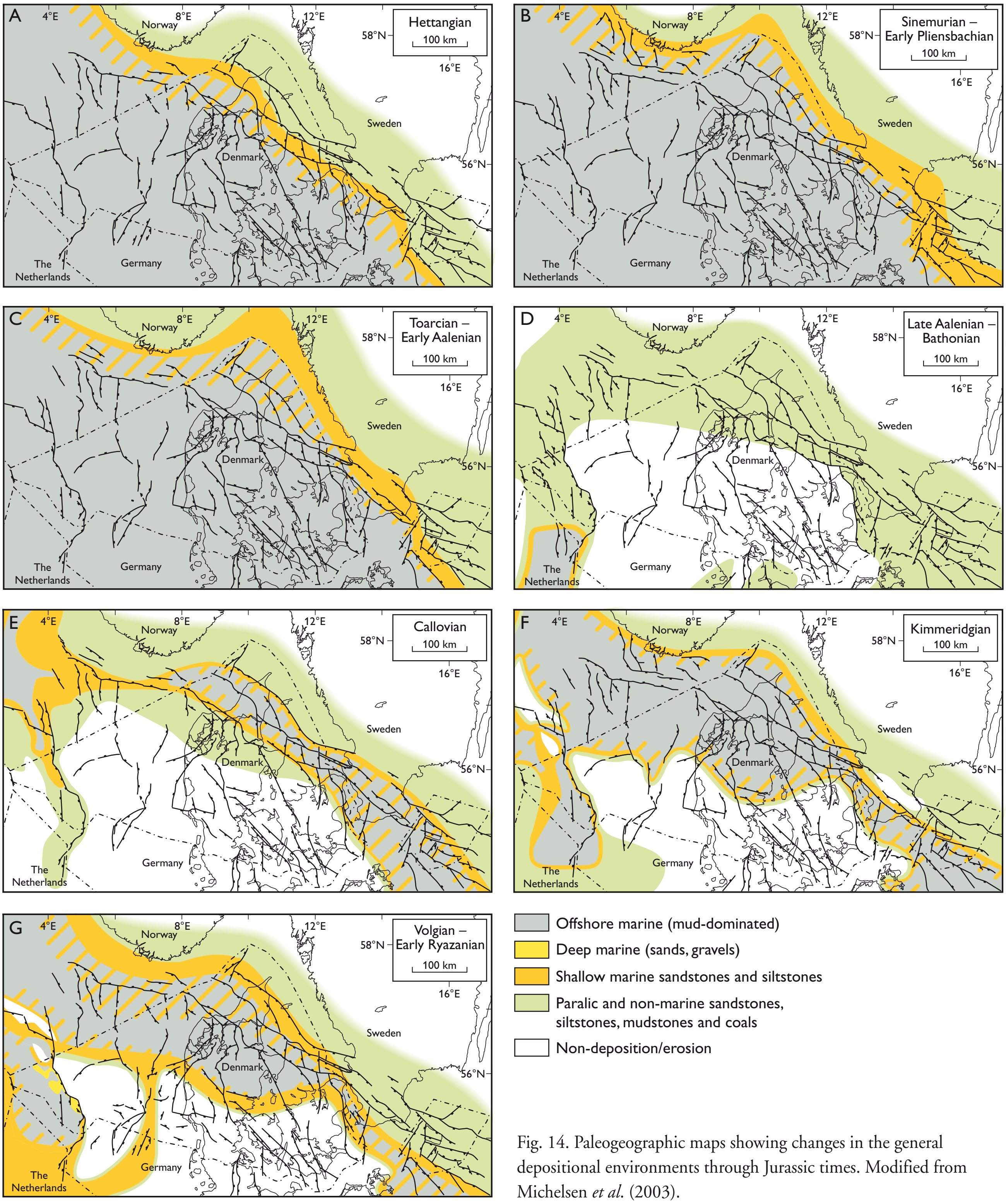


Fig. 14. Paleogeographic maps showing changes in the general depositional environments through Jurassic times. Modified from Michelsen *et al.* (2003).

since they intersect positive Jurassic structures that were exposed to deep erosion during regional uplift. In the Egersund Basin, located on-strike farther to the north-west (Fig. 1), the Fjerritslev Formation is also deeply truncated and is locally absent. Erosion did not reach such deep levels closer to the Sorgenfrei–Tornquist Zone (Fig. 15). Within the fault-bounded Sorgenfrei–Tornquist Zone itself, where subsidence still occurred (but at a much lower rate than before), the dramatic changes in regional basin configuration are marked by a shift from offshore mudstones

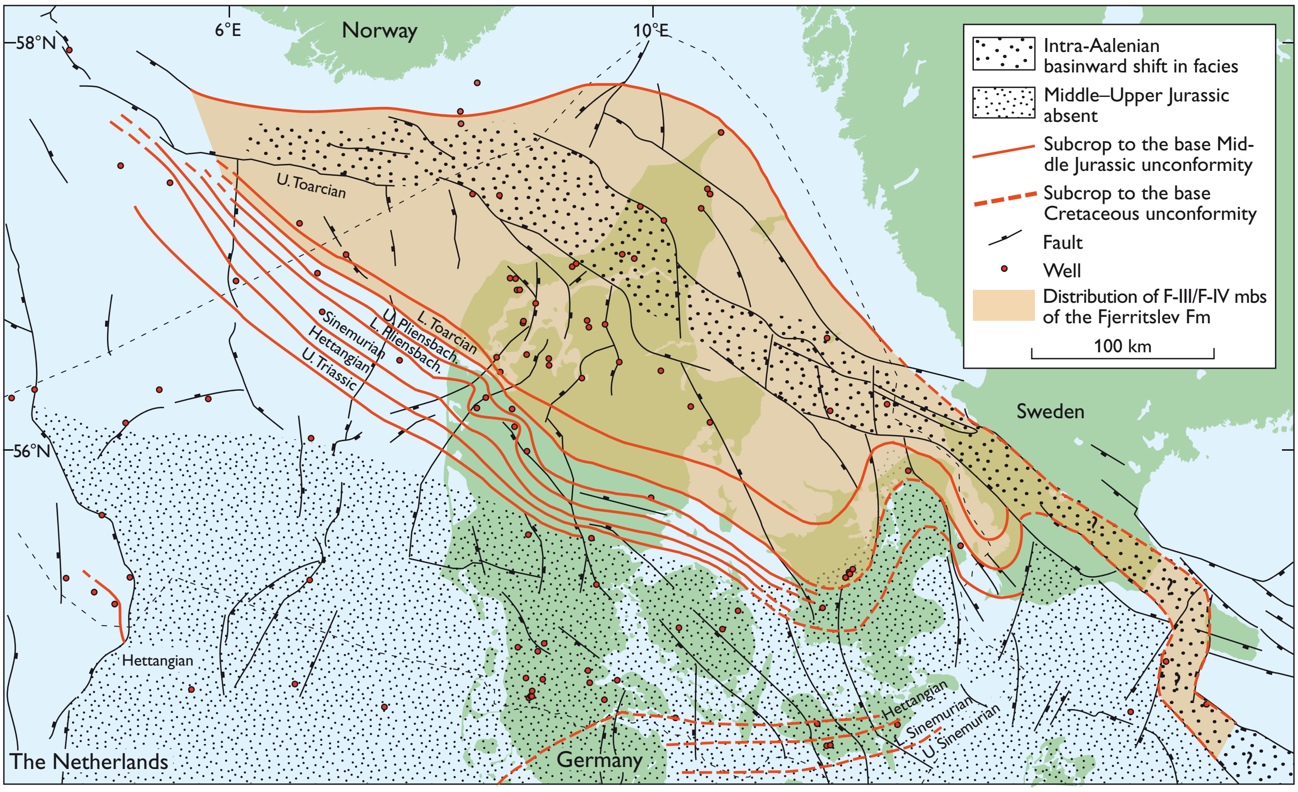


Fig. 15. The subcrop below the base Middle Jurassic unconformity and the distribution of the stratigraphic interval with the Lower Jurassic potential source rocks (F-III and F-IV members). The coarse-dotted area indicates the area within which the shift from marine mudstones to shallow marine or fluvial sandstones occurred in the Aalenian without major erosion. Modified from Nielsen (2003).

of the F-IV member (Fjerritslev Formation) to shallow marine sandstones (Haldager Sand Formation; Figs 8, 12–16). During the rest of the Aalenian, the Bajocian and the early Bathonian, deposition was more or less confined to the narrow zone bounded by the Fjerritslev and Børglum Faults and their south-eastward continuation in the Kattegat, Øresund and southern Sweden (Figs 8, 14). It is assumed that the westward continuation of the faults defining the southern margin (the Fjerritslev Fault) and the northern margin of the Farsund Basin also delineate an area of continued subsidence in Middle Jurassic times, thus protecting the potential source rocks in the upper Fjerritslev Formation from erosion in that area. The Fjerritslev Trough and presumably also the Farsund Basin received detritus from the uplifted areas to the west and south-west, and from the Baltic Shield to the north, resulting in deposition of the Haldager Sand Formation, which is 29–155 m thick in the well sections in the Fjerritslev Trough (Figs 8, 9, 16). The formation is dominated by shoreface and fluvial sandstones interbedded with thin marine and lacustrine mudstones, and thin coaly beds in places.

Late Middle – Late Jurassic basin expansion

Regional subsidence resumed during late Middle – Late Jurassic times and the shallow marine clastic depocentre gradually expanded. The Upper Jurassic thus onlaps onto the base Middle Jurassic unconformity, showing significant younging of the onlap towards the south-west and north-east, on both sides of the Sorgenfrei–Tornquist Zone (Figs 14, 17). Deposition overstepped the bounding faults of the Sorgenfrei–Tornquist Zone, with deposition of Bathonian(?) braided fluvial sands on the Skagerrak–Kattegat Platform and in the Himmerland Graben. Deposition also resumed outside the study area where Bathonian(?) sandstones of the Haldager Sand and Bryne Formations are preserved in the 10/7-1 and 10/8-1 wells.

A marine transgression close to the Callovian–Oxfordian boundary influenced most of the basin, and accommodation space was also created in the former by-pass zone of the southern part of the basin and on the Skagerrak–Kattegat Platform, where fluvial sands were deposited. During the

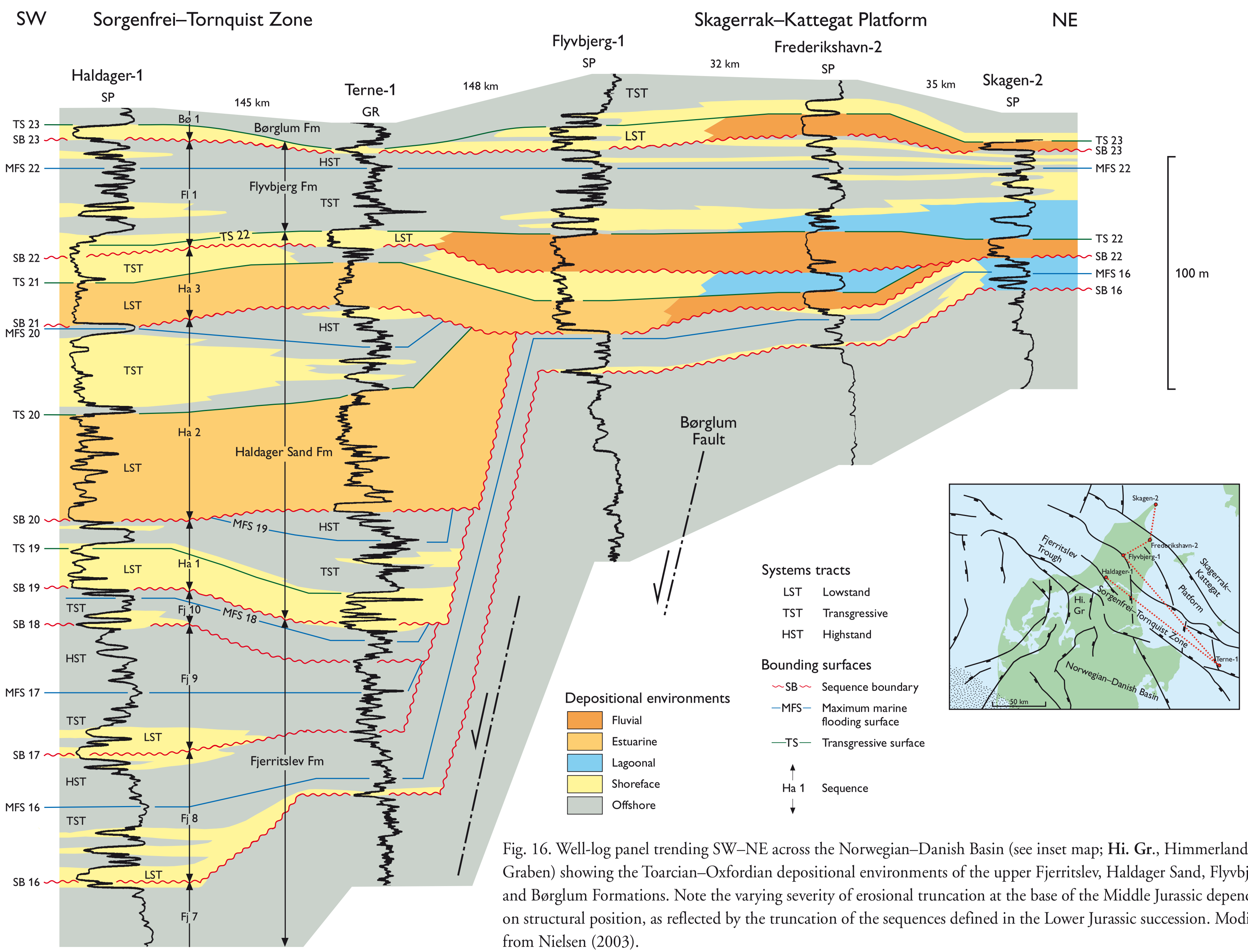


Fig. 16. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Toarcian–Oxfordian depositional environments of the upper Fjerritslev, Haldager Sand, Flyvbjerg and Børglum Formations. Note the varying severity of erosional truncation at the base of the Middle Jurassic depending on structural position, as reflected by the truncation of the sequences defined in the Lower Jurassic succession. Modified from Nielsen (2003).

Oxfordian, the sedimentation area was further enlarged, and a north-eastwards thickening wedge of transgressive, fossiliferous marine sand and mud was deposited above lagoonal deposits on the Skagerrak–Kattegat Platform (lower Flyvbjerg Formation; Figs 8, 9, 13, 16). The transgression peaked in the mid-Oxfordian, with deposition of marine mudstones over most of the northern part of the study area including the Fjerritslev Trough and the Skagerrak–Kattegat Platform. A sea-level fall in the latest Oxfordian resulted in coastal progradation on the Skagerrak–Kattegat Platform and in the Fjerritslev Trough; fluvial and shallow marine sands were deposited, and a south-west prograding wedge was formed (upper Flyvbjerg Formation; Figs 8, 9, 16).

Extensive marine flooding occurred in Kimmeridgian times, and sedimentation of marine mud (Børglum Formation) characterised the whole area, although marked thinning towards the south-west of the study area emphasises the reduced accommodation space there (Figs 8, 12–14, 16). During Volgian–Ryazanian times, the depositional environment was dominantly a shallow shelf, with three to four major phases of coastal progradation (sequences Fr 1–3 of the Frederikshavn Formation; Figs 8, 14). Marine muds were deposited over much of the study area.

Cretaceous continued basin expansion and chalk deposition

In Early Cretaceous times, the area of marine deposition expanded further with coastal progradation from the north and north-east. Deposition of marine mud prevailed over most of the study area. The Lower Cretaceous mudstones with sandy intercalations (most common towards the north-east) are included in the Vedsted Formation (Fig. 9), which consists of four depositional units (Michelsen & Nielsen 1991).

In Late Cretaceous – Danian times, a high sea level dominated and the study area was covered by an epicontinental sea. The dry climate and low relief of the hinterland reduced clastic input, and biogenic, pelagic chalk deposition (with coccolith plates being the dominant constituent) occurred over the entire study area. In the easternmost part of the basin and within the Fennoscandian Border Zone, deposition of marine greensands ceased in late Cenomanian times and in the Early Turonian intermittent deposition of marls and mudstones in parts of the basin also came to an end (Stenestad 1972; Surlyk 1980). In central parts of the study area, in the deepest parts of the Cretaceous basin, coc-

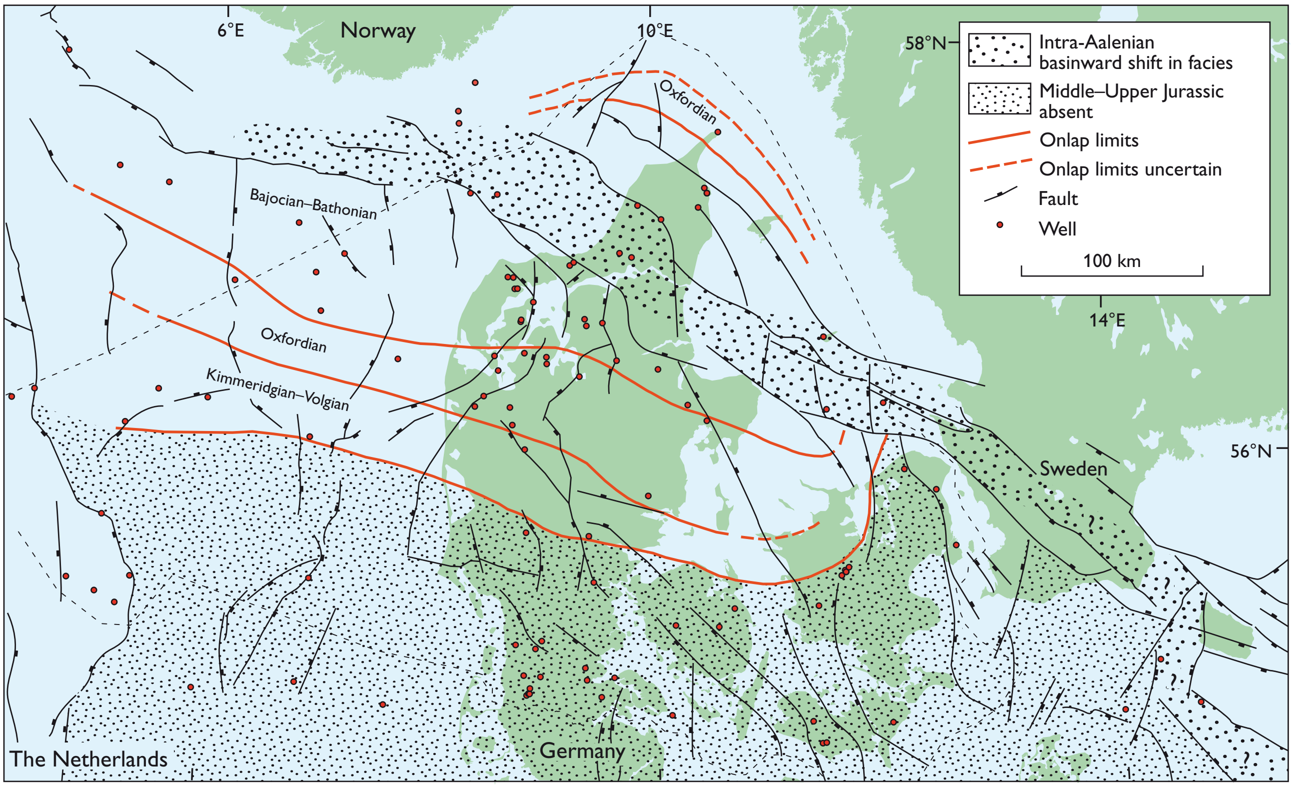


Fig. 17. Map showing the Upper Jurassic – Lower Cretaceous onlap onto the base Middle Jurassic unconformity, indicating the gradual expansion of the depositional area. Modified from Nielsen (2003).

colith-dominated chalks accumulated in water depths that may have been up to 500–600 m (Surlyk & Lykke-Andersen 2007). Closer to the basin margins and over structural highs, chalks rich in bryozoans and other benthic fossils were deposited at mid to inner shelf depths (?100–200 m). In more shallow water areas in the Fennoscandian Border Zone, benthos-rich chalks pass into bryozoan wackestones and packstones that locally developed as mound complexes, while skeletal grainstones and oyster bank carbonates formed closer to the shoreline (Surlyk 1997).

Centrally in the study area, south-west of the Sorgenfrei–Tornquist Zone, 1.5–2 km of chalk was deposited, while 500–750 m accumulated over the Ringkøbing–Fyn High. In the Sorgenfrei–Tornquist Zone, the original thickness of the chalk succession is masked by Late Cretaceous – Palaeogene inversion and erosion (Liboriussen *et al.* 1987; Nielsen & Japsen 1991; Jensen & Schmidt 1993; Michelsen & Nielsen 1993; Erlström & Sivhed 2001). The inversion began in Coniacian times and accelerated rapidly during Santonian–Campanian times (the sub-Hercynian phase; Ziegler 1990); quiescence during Maastrichtian–Danian times was followed by pronounced inversion again in the Late Paleocene (the Laramide phase; Liboriussen *et al.* 1987; Ziegler 1990).

Cenozoic clastic deposition and Neogene exhumation

After cessation of carbonate deposition in the Paleocene, deep marine sedimentation of fine-grained hemipelagic deposits took over in the study area. The northern and eastern limits of these fine-grained sediments are unknown due to later erosion. In the Oligocene, major clastic wedges began to build out from the Baltic Shield, while prodeltaic glauconite-rich clayey sediments were deposited farther basinwards. Coarse-grained sediments reached the southern part of the basin and the Ringkøbing–Fyn High in Neogene times (Larsen & Dinesen 1959; Friis *et al.* 1998; Rasmussen 2004). Deposition in the greater North Sea basin continued during the Pliocene, and up to 500 m of sediments were deposited in the Norwegian–Danish Basin during the Late Miocene and Pliocene (Overeem *et al.* 2001). During the post-Late Cretaceous period, parts of the Norwegian–Danish Basin and the Fennoscandian Border Zone were uplifted and eroded. This major tilting continued into the Quaternary (Japsen 1993; Jensen & Schmidt 1993; Japsen *et al.* 2002a, b; Rasmussen *et al.* 2005).

Regional coalification curves corrected for net exhumation

Due to Late Cretaceous – Early Cenozoic inversion of fault blocks in the Sorgenfrei–Tornquist Zone and Neogene–Pleistocene regional uplift of the Norwegian–Danish Basin (e.g. Michelsen & Nielsen 1991, 1993; Jensen & Schmidt 1993; Japsen 1993, 1998; Petersen *et al.* 2003a), present-day burial depths must be corrected for post-Early Cretaceous net exhumation (Fig. 18). Petersen *et al.* (2003a) presented a regional coalification curve for the Norwegian–Danish Basin based on 249 measurements from 15 wells (onshore wells and the Hans-1 well in the Kattegat). That study did not include offshore wells from the Skagerrak area. The well-sections were corrected for net-exhumation values obtained from the analysis of sonic velocities of shales by Japsen (1993). The accuracy of this method is dependent on a uniform shale unit covering the entire study area and a valid sonic velocity reference curve. Net exhumations for wells not included in Japsen's (1993) study were estimated by comparison to nearby wells and interpolation.

In the present study, new regional coalification curves for the Norwegian–Danish Basin have been constructed in order to evaluate the depth to the oil window. The depths of the samples have been corrected for net exhumation, the magnitudes of which have been derived from both shale and chalk velocities. A total of 560 vitrinite reflectance (VR) measurements from 26 wells in the Norwegian–Danish Basin were available for construction of the coalification curves (Fig. 18). The VR values are from Thomsen (1980, 1983), Schmidt (1985, 1988, 1989) and GEUS unpublished data. All VR values are random measurements performed on core samples, sidewall cores or cuttings, and as many particles as possible were measured in each sample. Untreated rock samples (whole rock) were used, as such samples – compared to kerogen concentrates – have the advantage that it is easier to identify the primary vitrinite particles and thus avoid oxidised and bituminous organic matter (e.g. Barker 1996). Identification of the primary, i.e. indigenous or autochthonous, vitrinite is essential for obtaining reliable VR values as this vitrinite reflects the actual ther-

Table 1. Net exhumation magnitudes*

Well	Shale†	Chalk†	Mean§	VR	Comments
Anholt-1	*1400*	*1400*	-	-	Comparison to Hans-1, Terne-1 and Frederikshavn-1 (very uncertain)
Års-1	442	461	-	-	
Børglum-1	1185	600	-	-	
C-1	*300*	306	-	-	Comparison to Inez-1 and Vemb-1 (264 m)
D-1	*50*	50	-	-	Comparison to L-1
F-1	481	357	419	1200	
Farsø-1	377	530	-	-	
Felicia-1/1A	1020	712	866	800	
Fjerritslev-2	1443	802	-	-	
Frederikshavn-1	*1000*	702	-	-	Comparison to Sæby-1 (1051 m)
Gassum-1	*1090*	579	-	-	Comparison to Voldum-1 (845 m) + 250 m deeper chalk truncation
Haldager-1	*1400*	486	-	-	Comparison to Børglum-1 and Fjerritslev-2
Hans-1	1735	-	-	-	
Hobro-1	*450*	543	-	-	Comparison to Års-1 and Kvols-1
Hyllebjerg-1	470	552	-	-	
Inez-1	344	445	395	850	
K-1	624	414	519	1300	
Kvols-1	361	420	-	-	
L-1	0	0	-	-	
Mors-1	690	602	-	-	
R-1	*150*	176	-	-	Comparison to C-1, L-1, S-1 (0 m) and Vemb-1 (238 m)
Rønde-1	394	447	-	-	
Skagen-2	*1000*	*1000*	-	-	Comparison to Børglum-1, Frederikshavn-1 and Sæby-1 (1051 m)
Terne-1	1373	-	-	-	
Vedsted-1	*1300*	*500*	-	-	Comparison to Børglum-1, Fjerritslev-2 and Haldager-1
Vinding-1	*175*	*250*	-	-	Comparison to Mejrup-1 (sh: 231 m; ch: 253 m) and Vemb-1 (sh: 264 m; ch: 238 m)

* Net exhumation magnitudes based on shale and chalk sonic velocity data (Japsen *et al.* 2007)

† Magnitudes in italics are estimated; see comments column

§ Mean of shale (sh) and chalk (ch)

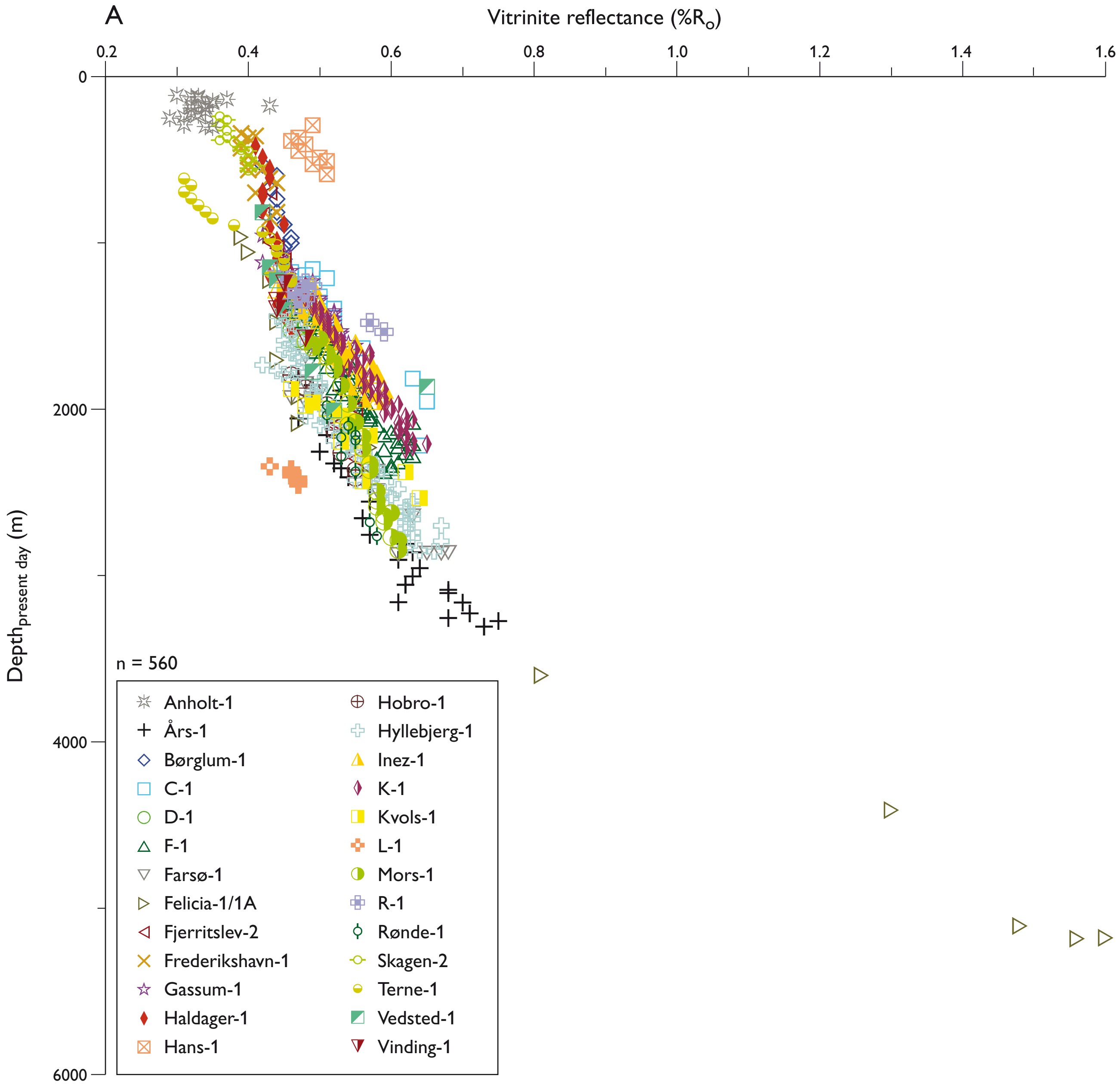


Fig. 18. **A**: Vitrinite reflectance values plotted against present-day depths for 26 onshore and offshore wells.

mal maturity of the organic matter at the sampled depth. Higher reflecting vitrinite particles may represent recycled organic matter that attained higher maturity from the temperature history of its former host rock (e.g. Bostick 1979; Hunt 1996; Taylor *et al.* 1998). In contrast, vitrinite that yields anomalously low reflectance values may be suppressed (Buiskool Toxopeus 1983; Carr 2000a, b). A more detailed description of the prerequisites for construction of a regional coalification curve is presented in Petersen *et al.* (2003a).

Shale velocity-based curve

The shale sonic velocity reference curve of Japsen (1993) has recently been refined and new, modified net-exhumation values based on shale velocities have been proposed (Table 1; Japsen *et al.* 2007). The revised magnitudes of net exhumation are reduced by about 100 m compared to the values used by Petersen *et al.* (2003a). The new net-exhumation values have been used to revise the coalification curve

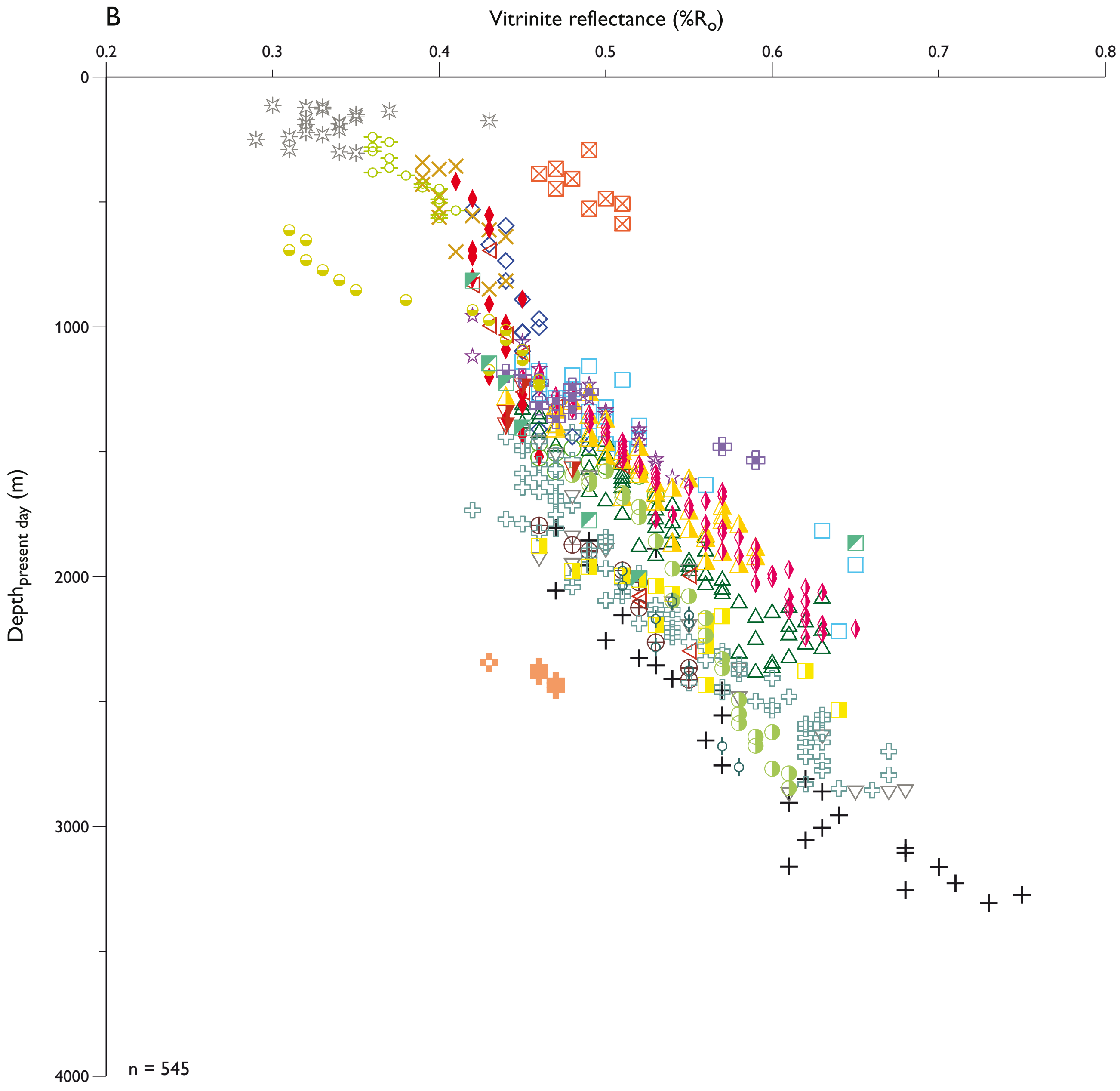


Fig. 18. **B:** As in 18A, but excluding the Felicia-1/1A deep well; for legend, see Fig. 18A.

for the study area. In Fig. 19, the present depths of samples from 25 wells have been corrected for the magnitudes of net exhumation obtained from shale velocities. For some wells, net-exhumation values based on shale velocities are not available, and the amount of net exhumation for these wells has been estimated by comparison to nearby wells and stratigraphic evaluation (Table 1). Despite the VR data showing considerable scatter, 13 of the wells define a well-constrained VR trend (Fig. 20A). Following Petersen *et al.* (2003a), the Fjerritslev-2, Haldager-1 and Vedsted-1 wells from the Fjerritslev Trough are not included as they define an atypically steep maturation gradient. This was explained by a probable overestimation of shale velocities in this area due to an increased coarse-grained component within the lowermost Fjerritslev Formation. The Anholt-1 and Terne-1 wells show unusually low VR values and are thus not included. Compared to the curve in Petersen *et al.* (2003a), the Horsens-1, Lavø-1 and Ullerslev-1 wells have been

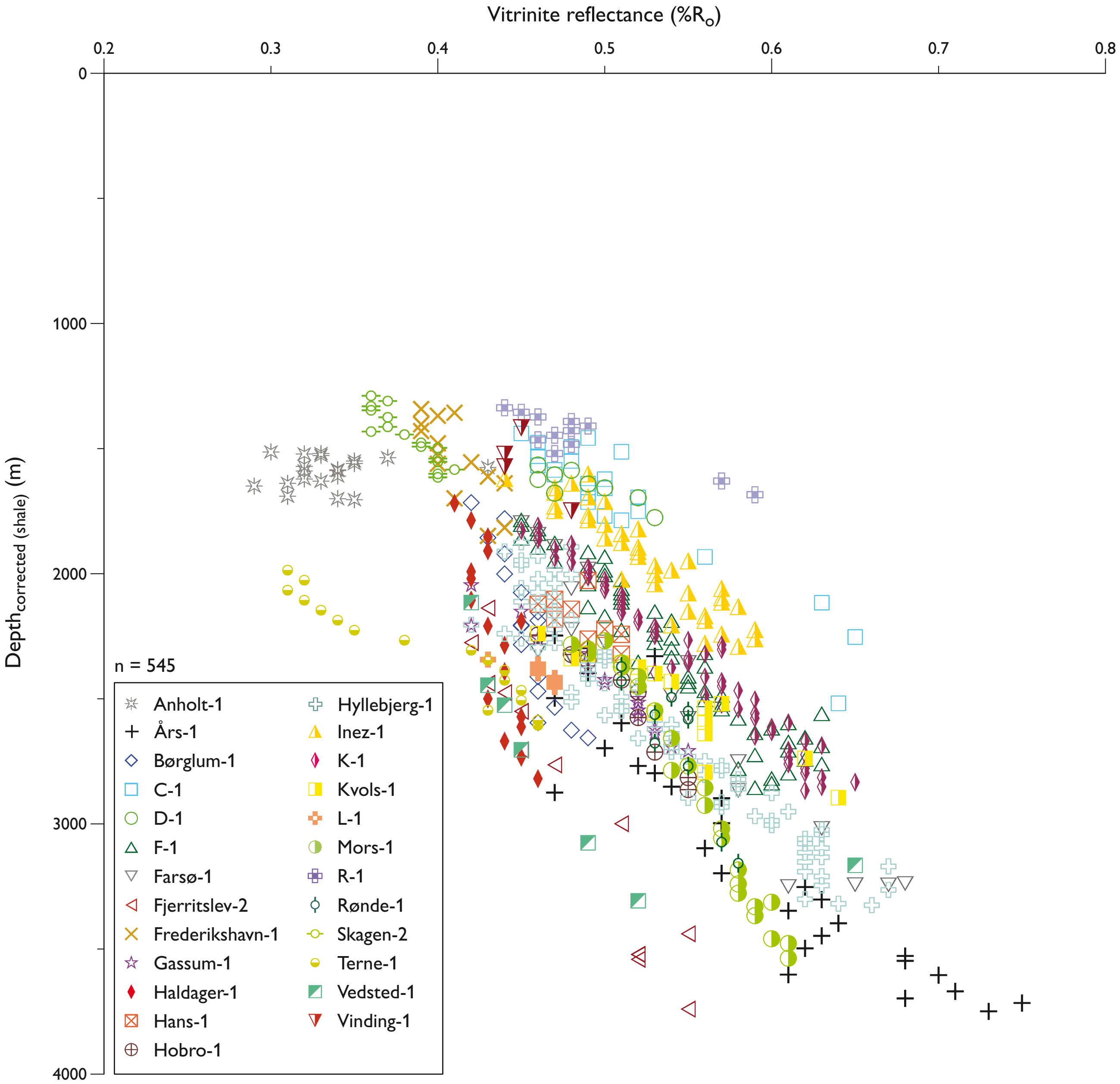


Fig. 19. Vitrinite reflectance values from 25 wells plotted against depths corrected for post-Early Cretaceous uplift on the basis of shale sonic velocity data.

omitted, as only one VR measurement is available from each well. The VR data from the Børglum-1 well are, however, included in the new coalification profile. Accurately determined VR values will define a straight line in a semi-log plot (Dow 1977), and the established VR profile yields a correlation coefficient of 0.89 (Fig. 20A). The linear regression line intercepts the surface at a VR of *c.* 0.26%R$_o$ which is at the upper end of the reflectance values recorded for peaty organic matter at the surface (*c.* 0.10–0.25%R$_o$; Cohen *et al.* 1987). If the start of the oil window is set at a VR of *c.* 0.6%R$_o$, the 'shale curve' suggests that the top of the oil window occurs at a burial depth of *c.* 3050 m.

VR data from offshore wells in the Skagerrak are not included in the coalification curve (Fig. 20A). Generally, the VR values from these wells lie above the maturity curve (Fig. 19), and data from four of the wells (D-1, F-1, Inez-1 and K-1) provide a relatively well-defined VR trend (Fig. 20B). The regression line yields a correlation coefficient of 0.80 and intercepts the surface at a VR of *c.* 0.28%R$_o$. This alternative maturity gradient may be applied for the off-

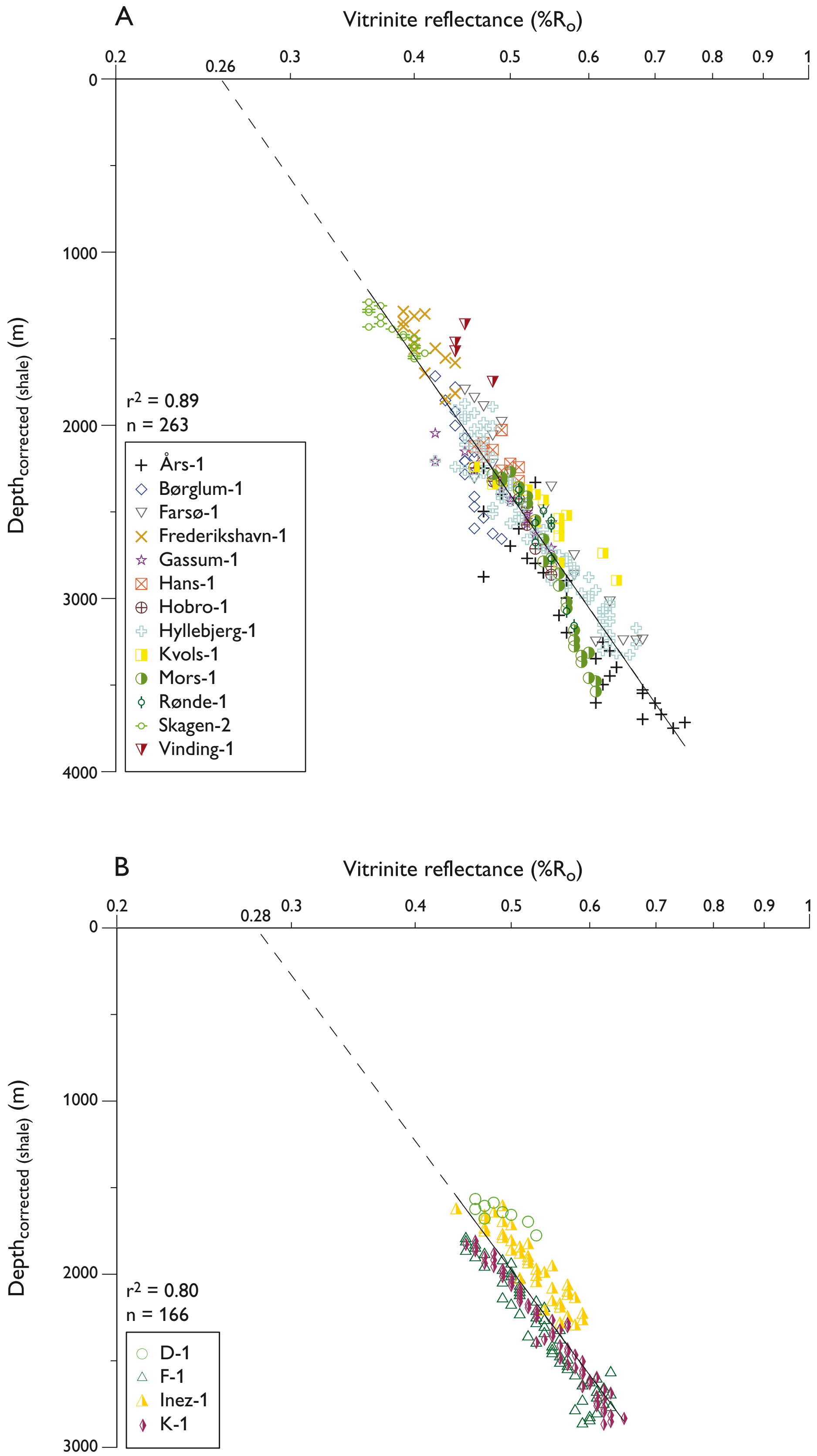


Fig. 20. **A:** Regional coalification curve for the Norwegian–Danish Basin based on 12 onshore wells and the Hans-1 well, selected from the wells in Fig. 19 (see text). A total of 263 vitrinite reflectance values have been used. The regression line has a correlation coefficient of $r^2 = 0.89$ and the line intercepts the surface at 0.26%R$_o$. The depth to the top of the oil window at 0.6%R$_o$ is *c.* 3050 m. **B:** Coalification curve based on four wells from the Skagerrak area. The regression line yields a correlation coefficient of 0.80 and the line intercepts the surface at a VR of *c.* 0.28%R$_o$. The top of the oil window (VR *c.* 0.6%R$_o$) occurs at a burial depth of *c.* 2600 m according to this curve.

shore part of the study area. According to this curve, however, the top of the oil window (VR *c.* 0.6%R_o) occurs at a burial depth of *c.* 2600 m which, given the absence of petroleum discoveries in this part of the basin, is probably too shallow. Underestimation of the magnitude of exhumation in the area may provide an explanation for the apparently erroneous curve.

Chalk velocity-based curve

Chalk velocities have – like shale velocities – been used to estimate the magnitude of net exhumation by Japsen (1998). Considerable uncertainty in the estimated exhumation may be introduced if the chalk section is <300 m thick. Net-exhumation magnitudes based on new chalk velocities (Japsen *et al.* 2007) have been used to correct the present-day sample depths in this study (Table 1). Compared to the net-exhumation magnitudes in Japsen (1998), the adjusted values presented here are reduced by about 200 m. In Fig. 21, the present depths of samples from 25 wells have been corrected for the magnitudes of net exhumation obtained from chalk velocities. The VR data show a relatively large scatter, although the data seem to group into two elongate populations with the upper population principally formed by offshore wells in the Skagerrak. The linear regression line for a regional VR curve based on 15 onshore wells and the Hans-1 well has a correlation coefficient of 0.87 (Fig. 22A), which is slightly poorer than the 'shale curve'. The linear regression line is, however, based on more data (n = 282) as VR data from the Fjerritslev-2 and Vedsted-1 wells are included in the coalification profile. Like the 'shale curve', the Haldager-1 well yields an abnormally steep maturity gradient, while the Anholt-1 and Terne-1 wells display much too low VR values compared to the overall trend defined by the majority of wells (Fig. 21). The curve intercepts the surface at a VR of *c.* 0.28%R_o, which is at the upper end of the VR values of peaty organic matter (Fig. 22A). Compared to the 'shale curve', the slightly lower gradient of the 'chalk curve' yields a burial depth of *c.* 3100 m for the top of the oil window using a VR of 0.6%R_o.

As with the shale velocity-corrected samples, the chalk velocity-corrected samples from offshore wells in the Skagerrak yield VR values that generally lie above the established maturity profile (Fig. 21). Three of these wells (F-1, Inez-1, K-1) provide a well-constrained VR gradient (correlation coefficient of 0.90) that intercepts the surface at *c.* 0.26%R_o (Fig. 22B). According to this curve, the top of the oil window is located at about 2450 m depth, which is considered an unrealistically shallow burial depth probably due to underestimation of the magnitude of exhumation.

Depth to the top of the oil window

If the top of the oil window is set at a maturity level corresponding to *c.* 0.6%R_o, the two depth-corrected maturity gradients, derived from the onshore wells, yield similar depths to the top of the oil window (*c.* 3050–3100 m). According to the relationship between VR and burial peak temperature of Barker & Pawlewicz (1994), *c.* 0.6%R_o corresponds to *c.* 95°C. This fits reasonably well with the present-day thermal gradient of 31.4°C/km in Felicia-1/1A, as estimated from corrected bottom-hole temperature measurements. In contrast, depth-corrected maturity gradients based on offshore wells from the Skagerrak yield unrealistically shallow burial depths to the top of the oil window. Burial depths of only 2450–2600 m would imply the presence of mature source rocks in the area, which is inconsistent with the lack of direct evidence of generated petroleum.

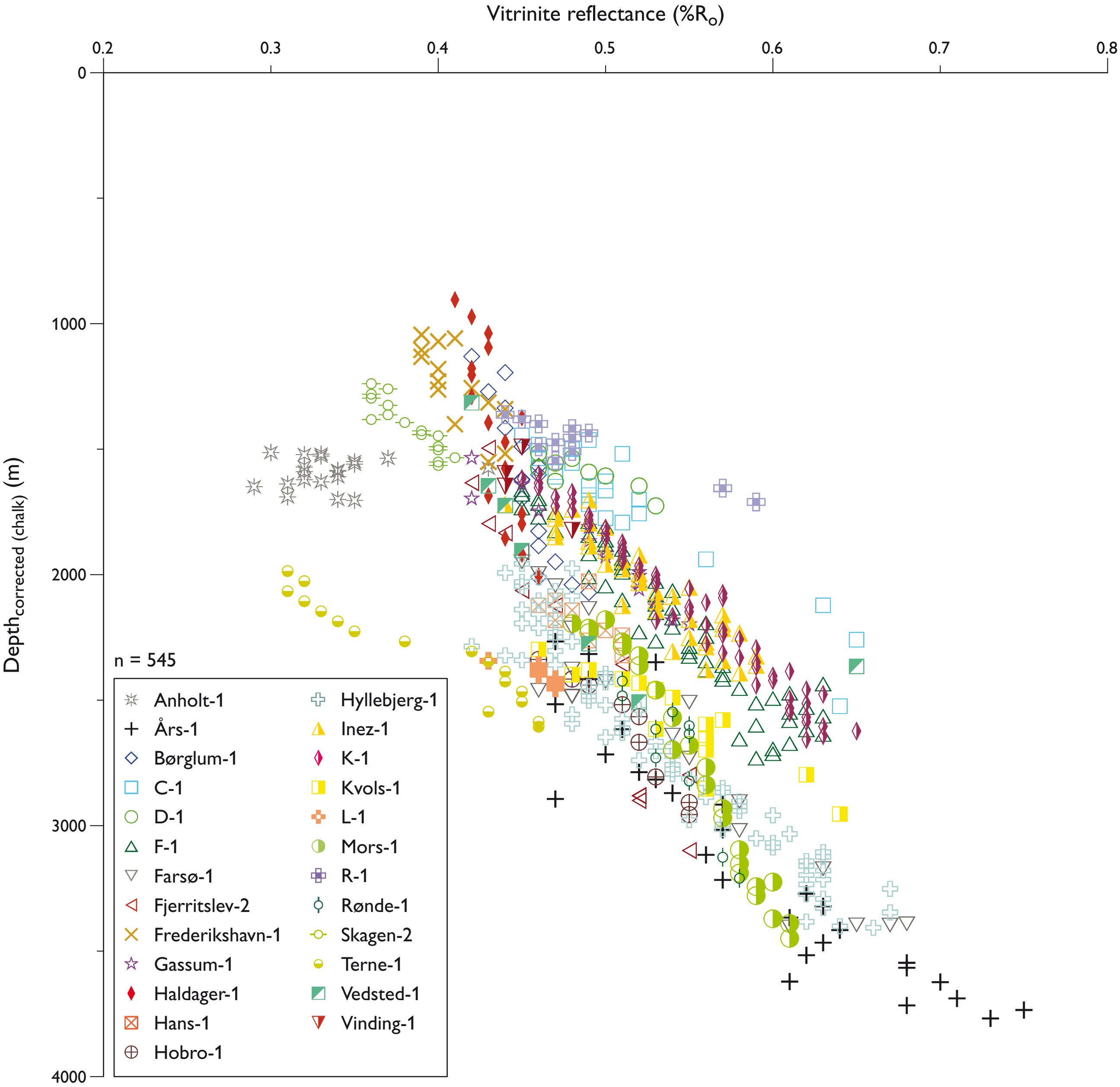
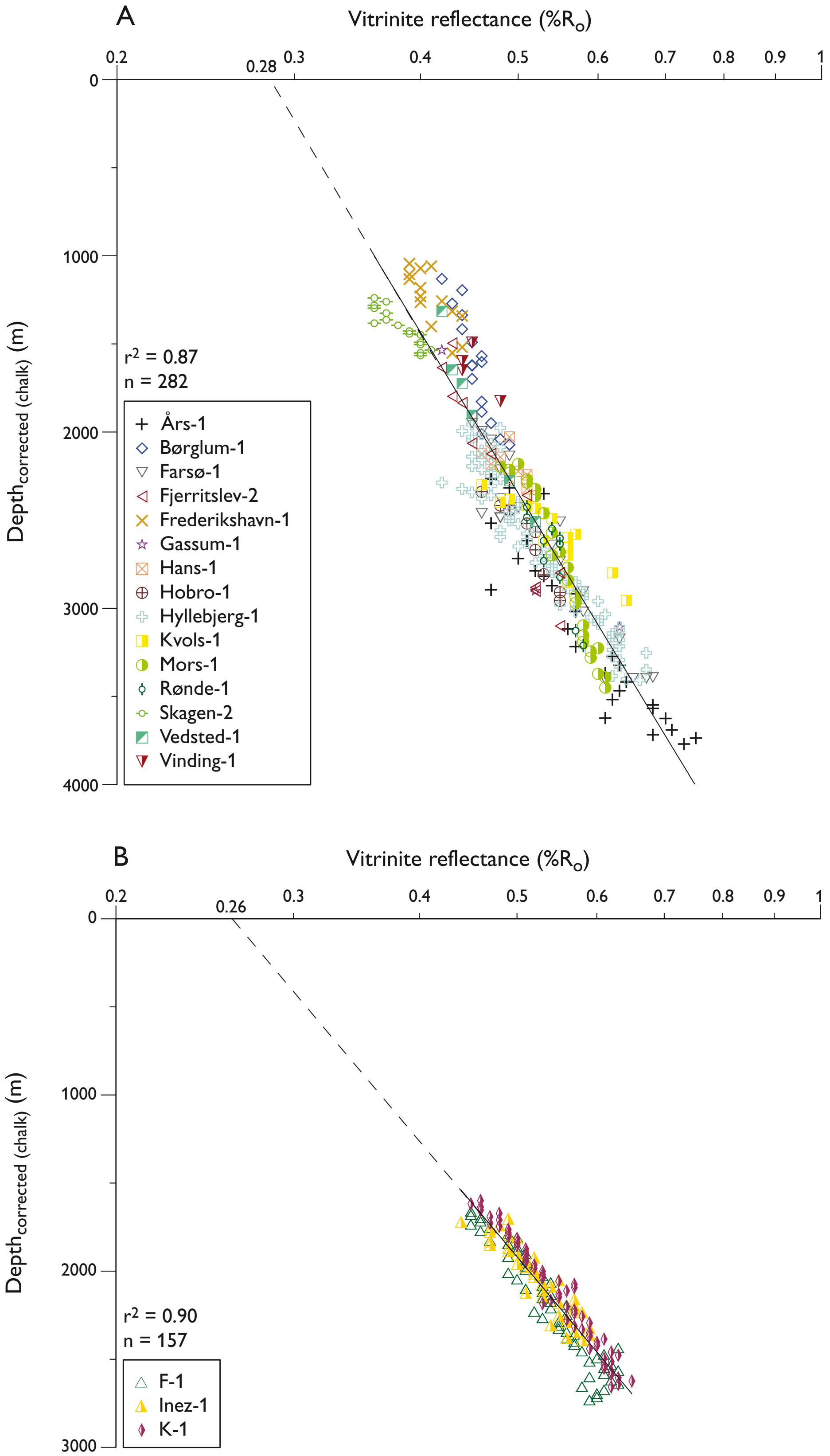


Fig. 21. Vitrinite reflectance values from 25 wells plotted against depths corrected for post-Early Cretaceous uplift on the basis of chalk sonic velocity data.

Fig. 22. **A**: Regional coalification curve for the Norwegian–Danish Basin based on 14 onshore wells and the Hans-1 well, selected from the wells in Fig. 21 (see text). A total of 282 vitrinite reflectance values have been used. The regression line has a correlation coefficient of $r^2 = 0.87$ and the line intercepts the surface at 0.28%R_o. The depth to the top of the oil window at 0.6%R_o is *c.* 3100 m. **B**: Coalification curve based on three offshore wells from the Skagerrak area. The VR data form a very well-constrained VR gradient (correlation coefficient of 0.90) that intercepts the surface at *c.* 0.26%R_o. According to this curve, the top of the oil window is located at only *c.* 2450 m depth.



Distribution and thermal maturity of potential source rocks

The regional petroleum generation potential and thermal maturity of the pre-Upper Cretaceous succession in the study area have been assessed by the evaluation of more than 4000 data points (S_1 and S_2 yields, Hydrogen Index (HI), T_{max}, total organic carbon (TOC)). These are derived from Rock-Eval pyrolysis and TOC determination of principally cuttings samples from 33 wells situated onshore Denmark and offshore in the Skagerrak and Kattegat areas (Fig. 1). Most of the wells drilled the Lower Cretaceous – Triassic succession, but pre-Permian and Permian strata were also encountered in some wells.

Unreliable T_{max} or HI values derived from low S_2 yields (i.e. approximately <0.2 mg HC/g rock) or TOC contents have been omitted from the data set. The following thresholds for HI have been applied to evaluate the petroleum generation capacity of the predominantly Type II kerogen dominated source rocks (Peters & Cassa 1994):

HI <200 mg HC/g TOC: gas-prone
HI = 200–300 mg HC/g TOC: mixed oil/gas-prone
HI >300 mg HC/g TOC: oil-prone

Determination of the thermal maturity is based on vitrinite reflectance (VR) and T_{max} values, and the potential source rock is considered immature for VR values <0.6%R_o or T_{max} values <435°C. The T_{max} range 435–460°C defines the oil window (Bordenave *et al.* 1993; Peters & Cassa 1994). T_{max} is, however, also influenced by kerogen type and the mineral matrix, and single T_{max} values may therefore be less reliable as a maturity parameter (Peters 1986). Average T_{max} values for specific formations or members with source rocks are therefore used.

Pre-Permian units

Seven wells have encountered pre-Permian strata in the Danish part of the Norwegian–Danish Basin and Fennoscandian Border Zone. Source-rock data are available from five of them: Frederikshavn-1, Nøvling-1, Rønde-1, Slagelse-1 and Terne-1 (Fig. 1). Bitumen and oil stains have been reported from Lower Palaeozoic rocks onshore Norway and Sweden. In the Oslo Graben, bitumen has been found in fractures in Ordovician limestones and corals, and in southern Norway, close to the Oslo Graben, oil and gas are trapped in Permian volcanic intrusive rocks (Pedersen *et al.* 2005, 2007). In southern Sweden, at Österplana, oil has been found in Upper Ordovician carbonate rocks (Pedersen *et al.* 2007). Pedersen *et al.* (2005, 2007) suggested that the petroleum was generated from Lower Palaeozoic source rocks. Lower Palaeozoic source rocks and oils are known from the Baltic area, where Lower Silurian shales constitute the principal source (Zdanaviciuté & Bojesen-Koefoed 1997). Moreover, oil has been generated from Palaeozoic units in Sweden (Sivhed *et al.* 2004 and references therein).

The up to 90 m thick Middle Cambrian – Lower Ordovician Alum Shale, which is exposed in Skåne, on Bornholm and in southern Norway, possesses source-rock properties. The black marine shales are highly organic-rich with an organic matter content locally up to 30% (Thomsen *et al.* 1987; Bharati *et al.* 1992). In central Sweden, the Alum Shale is immature to marginally mature and has HI values up to above 600 mg HC/g TOC, but in the Fennoscandian Border Zone the shales are overmature (Buchardt *et al.* 1986; Buchardt & Lewan 1990; Bharati *et al.* 1992). The Alum Shale was encountered in the Slagelse-1 and Terne-1 wells. In the Slagelse-1 well, TOC contents are below the reliable detection limit of the carbon analyser, but in the Terne-1 well, TOC contents range from 5.39–10.08 wt%. The Alum Shale in the Terne-1 and Slagelse-1 wells is, however, overmature, with HI values <8 mg HC/g TOC in the Terne-1 well.

High TOC contents and HI values were recorded in the Upper Silurian Nøvling Formation in the Rønde-1 well, where the formation consists of interbedded basalts, grey and red-brown claystones and sandstones with some carbonates (Christensen 1971, 1973). The samples are, however, contaminated by various drilling mud additives, such as diesel, Black Magic®, and starch-based mud, which render the data unreliable.

Upper Carboniferous strata were encountered by the Hans-1 well, but no source-rock data are available. The drilled redbed section consists of interbedded sandstones, siltstones and claystones overlain by volcanic rocks and claystones, which are regarded to have no source-rock potential based on the lithology (Michelsen & Nielsen 1991, 1993). Upper Carboniferous coals are, however, significant gas source rocks regionally in Northwest Europe and the southern North Sea (Lokhorst 1998; Gautier 2003). West of the study area, the Carboniferous has been drilled by nine released wells in the Danish Central Graben and the southern part of the Norwegian and UK Central Graben; these strata are of Early Carboniferous age (Bruce & Stemmerik 2003). Thin Lower Carboniferous coals were encountered in the Gert-2 well, and these coals possess a gas/condensate generation potential inherited from the original vegetation, which is a general aspect of Carboniferous coals (Petersen 2006; Petersen & Nytoft 2006, 2007a, b). Reworked Carboniferous palynomorphs are common in the Jurassic of the Norwegian–Danish Basin suggesting that Carboniferous strata, probably coal-bearing, were originally more widespread (Nielsen & Koppelhus 1990) and may be preserved below the regional Permian unconformity in local deep grabens. These strata may thus potentially constitute a deep-seated source for gas/condensate.

In summary, the well data described here do not demonstrate the occurrence of viable source rocks in the pre-Permian succession. It should be acknowledged, however, that the Silurian is only known from the Rønde-1, Nøvling-1 and Terne-1 wells where less than 450 m of the up to 2600 m thick succession have been investigated (Christensen 1971, 1973; Michelsen & Nielsen 1991, 1993). Similarly, the distribution and nature of Carboniferous strata are very poorly known and it can be speculated that gas/condensate-prone Carboniferous strata may be preserved in local grabens and half-grabens, as recorded from the Central Graben (Bruce & Stemmerik 2003).

Permian units

Strata of Zechstein and Rotliegend age are present in nine wells, and results of source-rock analyses are available from five of them (C-1, Nøvling-1, Rønde-1, Slagelse-1, Sæby-1; Fig. 1). No petroleum generation has been observed in the analysed well sections. High TOC contents and HI values in the Rotliegend Group in the Rønde-1 well, where the formation is mainly composed of reddish brown sandstones (Jacobsen 1971; Nielsen & Japsen 1991), are artefacts from drilling mud additives.

Cuttings samples, showing a resemblance to black shale, from the Rotliegend section (5092–5260 m) in the Felicia-1A well, yield extraordinarily high HI values (exceeding 1000 mg HC/g TOC) and low T_{max} from 425–440°C (Petersen *et al.* 2003b). However, these data are flawed as the samples are contaminated by oil-based drilling mud (Shellsol D-70), which was used below a depth of about 2000 m. Core samples collected from thin black, shaly intervals yield HI values <32 mg HC/g TOC and T_{max} values from 480–494°C. This indicates overmaturity of the organic matter and no source potential. Visual inspection of the dispersed organic matter (DOM) by reflected light microscopy (white and fluorescing-inducing blue light) reveals lack of fluorescence of the DOM that is classified as vitrinite (Type III kerogen) and inertinite (Type IV kerogen). Lack of fluorescence and visible liptinitic material is in agreement with the high organic maturity. T_{max} values of 480–494°C correspond roughly to a vitrinite reflectance range of 1.6–1.9%R_o, and at this maturity level the fluorescence behaviour of all types of organic matter has disappeared. On the basis of presently available data, therefore, the Permian succession does not exhibit petroleum generation potential, although it is acknowledged that data are few and the Permian potential cannot be categorically discounted. Thin black, bituminous shales possibly equivalent to the Kupferschiefer in the North German Basin were encountered in the Rønde-1 well (Jacobsen 1971) and thin shales appear to be locally present in the Zechstein succession. The distribution of these facies in the Norwegian–Danish Basin is poorly known.

Triassic units

Triassic strata are dominated by continental to marginal marine sandstones, mudstones, marls, carbonates and evaporites, and good quality source rocks are not common in the Triassic. Petroleum generation potential has been detected in Upper Triassic strata in the Hans-1, Mejrup-1, Rønde-1 and Skagen-2 wells. A few HI values up to above 500 mg HC/g TOC have been recorded from mudstones of the marine Oddesund Formation in the Rønde-1 well, and in the Mejrup-1 well a *c.* 8 m thick interval in the brackish Vinding Formation has HI values up to nearly 700 mg HC/g TOC.

In the Hans-1 well, where parts of the Gassum Formation consist of aggrading parasequences of coastal plain deposits with coal beds, a *c.* 10 m thick interval possesses gas generation potential. In the Skagen-2 well, the uppermost part of the Gassum Formation and the lowermost part of the F-I member of the Fjerritslev Formation comprise lagoonal sediments with a restricted capacity to generate liquid petroleum (see below). In the Mejrup-1 well, the Gassum Formation is more fine-grained than normal, and certain mudstone intervals have HI values up to 534 mg HC/g TOC; the average HI value for a *c.* 73 m thick mudstone-dominated section is 216 mg HC/g TOC. This unusual development of the formation in Mejrup-1 is probably related to the position of the well in the secondary rim syncline of the Vejrum salt dome, in the centre of the basin. Movement of salt influenced depositional patterns at many locations in the basin, as shown by seismic data, but only few wells have drilled rim synclines and none show a development similar to that of the Gassum Formation in the Mejrup-1 well. However, detailed seismic mapping of the Upper Triassic may determine if similar depositional situations and sufficient burial of Upper Triassic potential

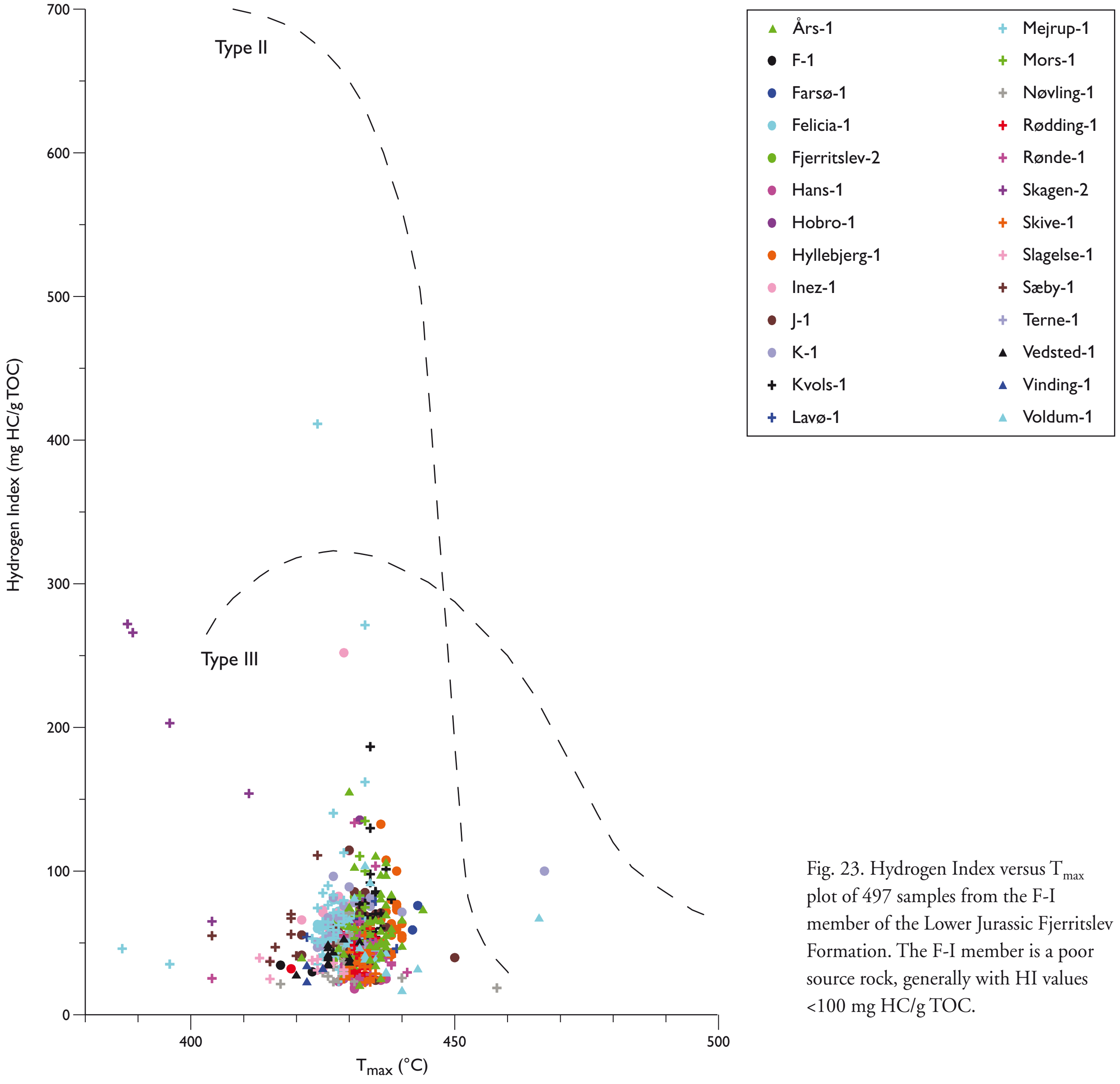


Fig. 23. Hydrogen Index versus T_{max} plot of 497 samples from the F-I member of the Lower Jurassic Fjerritslev Formation. The F-I member is a poor source rock, generally with HI values <100 mg HC/g TOC.

source rocks occur adjacent to other salt structures.

In summary, apart from a few local occurrences of Upper Triassic units with a limited potential, the Triassic does not possess a petroleum generation potential.

Lower Jurassic units

With the sole exception of the C-1 well, the Lower Jurassic offshore marine mudstones of the Fjerritslev Formation have been encountered in all the investigated wells. All four members of the Fjerritslev Formation (F-I – F-IV) are, however, not present in all wells due to Middle Jurassic uplift and erosion over much of the basin (Andsbjerg *et al.* 2001; Nielsen 2003). As a result of the uplift and associated erosion, the F-I member at the base of the formation is regionally the most widespread, being present in all but one well, whereas the F-IV member in the uppermost part of the formation is only present in 20 of the 33 wells. The F-II and F-III members are present in 25 of the wells.

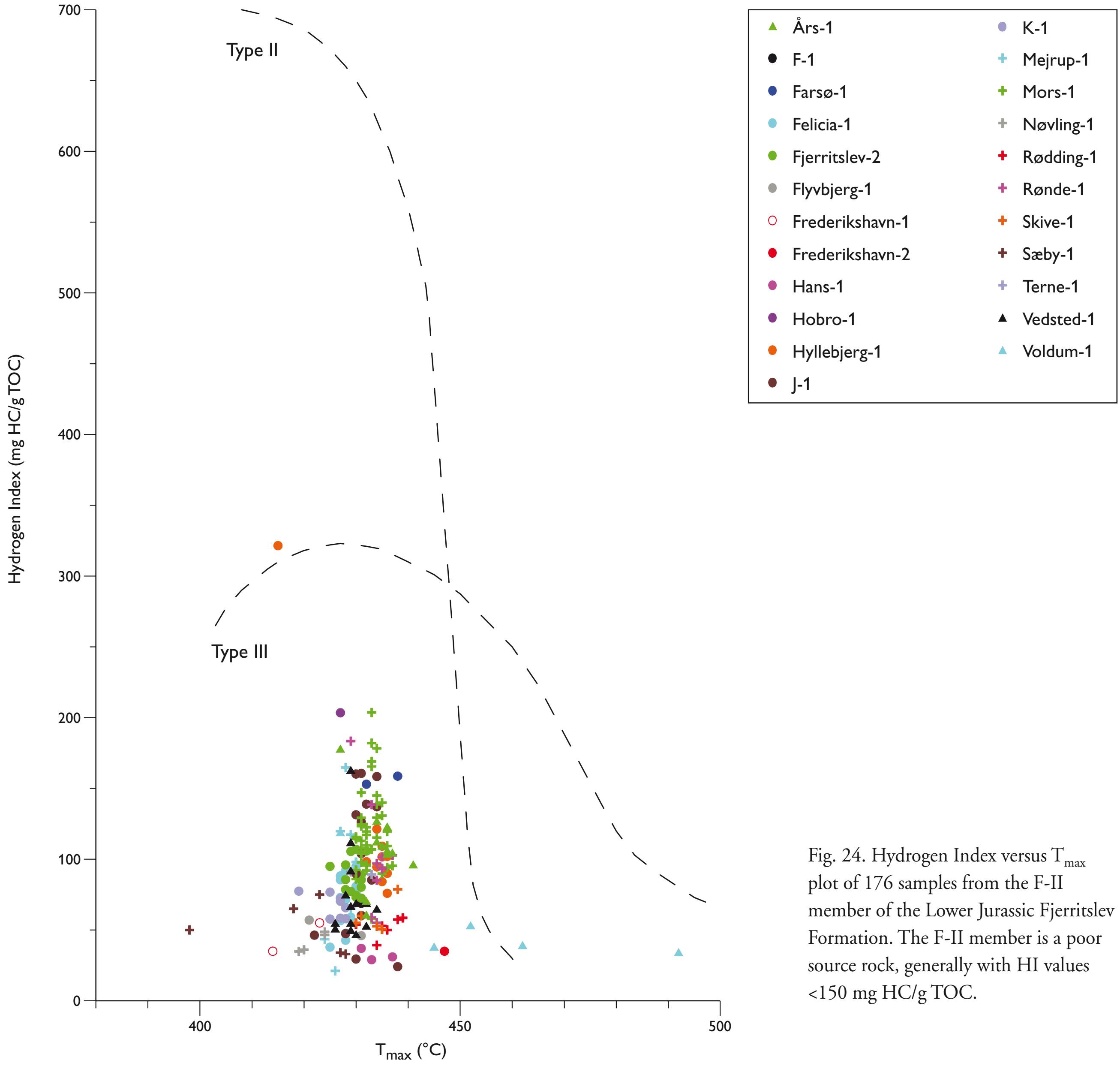


Fig. 24. Hydrogen Index versus T_{max} plot of 176 samples from the F-II member of the Lower Jurassic Fjerritslev Formation. The F-II member is a poor source rock, generally with HI values <150 mg HC/g TOC.

F-I member

Only in the Skagen-2 well does the F-I member possess a potential for petroleum generation (Fig. 23). As noted above (Triassic units), a 10 m thick interval spanning the uppermost part of the Gassum Formation and the lowermost part of the F-I member shows HI values ranging from 255–273 mg HC/g TOC. This interval is interpreted to consist of stacked lagoonal deposits that are only locally developed (Sequence Fj 9 of Nielsen 2003).

F-II member

A marginal petroleum generation potential has been recorded in the F-II member in the Farsø-1 and Mors-1 wells, whereas the member in the Hobro-1 well shows a somewhat better potential (Fig. 24), albeit over a very narrow interval. Within a 6 m thick interval in Hobro-1, the HI values range from 203–340 mg HC/g TOC. The topmost 10 m of the F-II member in Mors-1 has an average HI value of 183 mg HC/g TOC, whereas the average HI value of the member in Farsø-1 is 156 mg HC/g TOC. The F-II member in the latter two wells can thus principally be regarded as gas-prone. In the other wells, the mudstones of the F-II member possess no source-rock potential. Generally, the source-rock potential of the F-II member can thus be regarded as limited and primarily gas-prone.

F-III and F-IV members

The distribution of the F-III and F-IV members is controlled by post-depositional erosion related to the regional early Middle Jurassic uplift that influenced most of the Norwegian–Danish Basin and the Fennoscandian Border Zone. The map in Fig. 15 displays the area within which sediments of F-III or F-IV are preserved; in some wells the combined thickness of the F-III and F-IV members amounts to nearly 400 m (Fig. 25A; see also Table 2). The isopach map suggests that the largest combined thicknesses occur in the Himmerland Graben (Fig. 25B). The entire stratigraphic interval is only preserved in the Sorgenfrei–Tornquist Zone. The analyses of the 33 well sections show that the average quality of the F-III and F-IV members, in terms of potential source rocks for oil generation, is highly variable both stratigraphically and geographically (Figs 26, 27).

In the Kvols-1 and Rønde-1 wells, part of the F-III member constitutes an excellent potential oil source rock (Fig. 26). The uppermost alginite-bearing 40 m of the member in Kvols-1 has an average TOC content of 2.95 wt%, and the interval displays HI values consistently >300 mg HC/g TOC, with a maximum value of 529 mg HC/g TOC and an average value of 429 mg HC/g TOC (Fig. 28, 29A). The marine mudstones in this interval contain abundant algal-derived organic material composed of fluorescing, amorphous organic matter (AOM) and alginite of the *Tasmanites* and *Leiosphaeridia* types (Fig. 28). Associated framboidal pyrite testifies to the oxygen-deficient, organic-rich conditions in the sediment during deposition. This highly oil-prone section overlies a *c.* 25 m thick interval with an average HI value of 243 mg HC/g TOC. In Rønde-1, the topmost *c.* 18 m of the F-III member are highly oil-prone, with HI values ranging from 263–428 mg HC/g TOC, averaging 355 mg HC/g TOC (Fig. 29B). Similarly, the F-III member in the Haldager-1 well contains a *c.* 25 m thick oil-prone interval, with HI values reaching 425 mg HC/g TOC and averaging 323 mg HC/g TOC (Fig. 30A).

In a number of other wells, the F-III member also possesses a variable petroleum generation potential. The Farsø-1 and J-1 wells show maximum HI values around 300 mg HC/g TOC and average HI values of 214 mg HC/g TOC and 202 mg HC/g TOC, respectively, indicating a limited liquid petroleum generation potential (Fig. 30B). The Mors-1 well has an average HI value of the same order, but the maximum HI value only reaches 266 mg HC/g TOC (Fig. 31A). In the Hobro-1 well, a *c.* 12 m thick interval of the F-III member has an average HI of 233 mg HC/g TOC (Fig. 31B). The F-III member in Fjerritslev-2, Hyllebjerg-1 (Fig. 32A) and Voldum-1 (Fig. 32B) contains intervals with average HI values around 190 mg HC/g TOC, whereas in the Års-1 well, the average value is only 156 mg HC/g TOC. The F-III member of these latter four wells is considered to be principally gas-prone.

In the Rønde-1 well, the F-IV member (55 m thick) is an excellent, organic-rich (average TOC of 3.58 wt%), oil-prone source rock with an average HI value of 435 mg HC/g TOC and a maximum HI value of 543 mg HC/g TOC (Figs 27, 29B). The organic material in this highly oil-prone interval consists of abundant fluorescing AOM, detrital liptinite and *Leiosphaeridia* type alginite (Fig. 33). Both the AOM and detrital liptinite are probably composed of degraded algal material. The occurrence of framboidal pyrite is indicative of oxygen-deficient conditions during deposition of the organic-rich shales. A nearly 50 m thick section of the F-IV member in the Hyllebjerg-1 well has an average HI value of 210 mg HC/g TOC, with a maximum HI value of 371 mg HC/g TOC (Fig. 32A).

Table 2. Net source-rock (SR) thicknesses, F-III and F-IV members of the Fjerritslev Formation

Well	F-III Net SR (m)	F-III Gross (m)	F-III Net/gross	F-IV Net SR (m)	F-IV Gross (m)	F-IV Net/gross	Sum Net SR (m)	Sum Gross (m)	Sum Net/gross	Average HI*, Net SR interval (number of samples)
Haldager-1	31	117	0.26	9	127	0.07	40	244	0.16	294 (7)
Hobro-1	19	154	0.12	7	32	0.22	26	186	0.14	229 (4)
Hyllebjerg-1	35	228	0.15	21	55	0.38	56	283	0.20	246 (14)
J-1	19	98	0.19	0	43	0	19	141	0.13	267 (2)
Kvols-1	79	201	0.39	4	18	0.22	83	219	0.38	369 (28)
Mors-1	118	147	0.80	5	25	0.20	123	172	0.72	221 (17)
Rønde-1	48	145	0.33	44	55	0.80	92	200	0.46	404 (12)
Skagen-2	7	59	0.12	0	29	0	7	88	0.08	203 (1)
Sæby-1	0	53	0	4	38	0.11	4	91	0.04	261 (1)
Voldum-1	14	111	0.13	0	0	0	14	111	0.13	215 (2)

* Average HI in Net SR intervals based on HI values ≥200 mg HC/g TOC

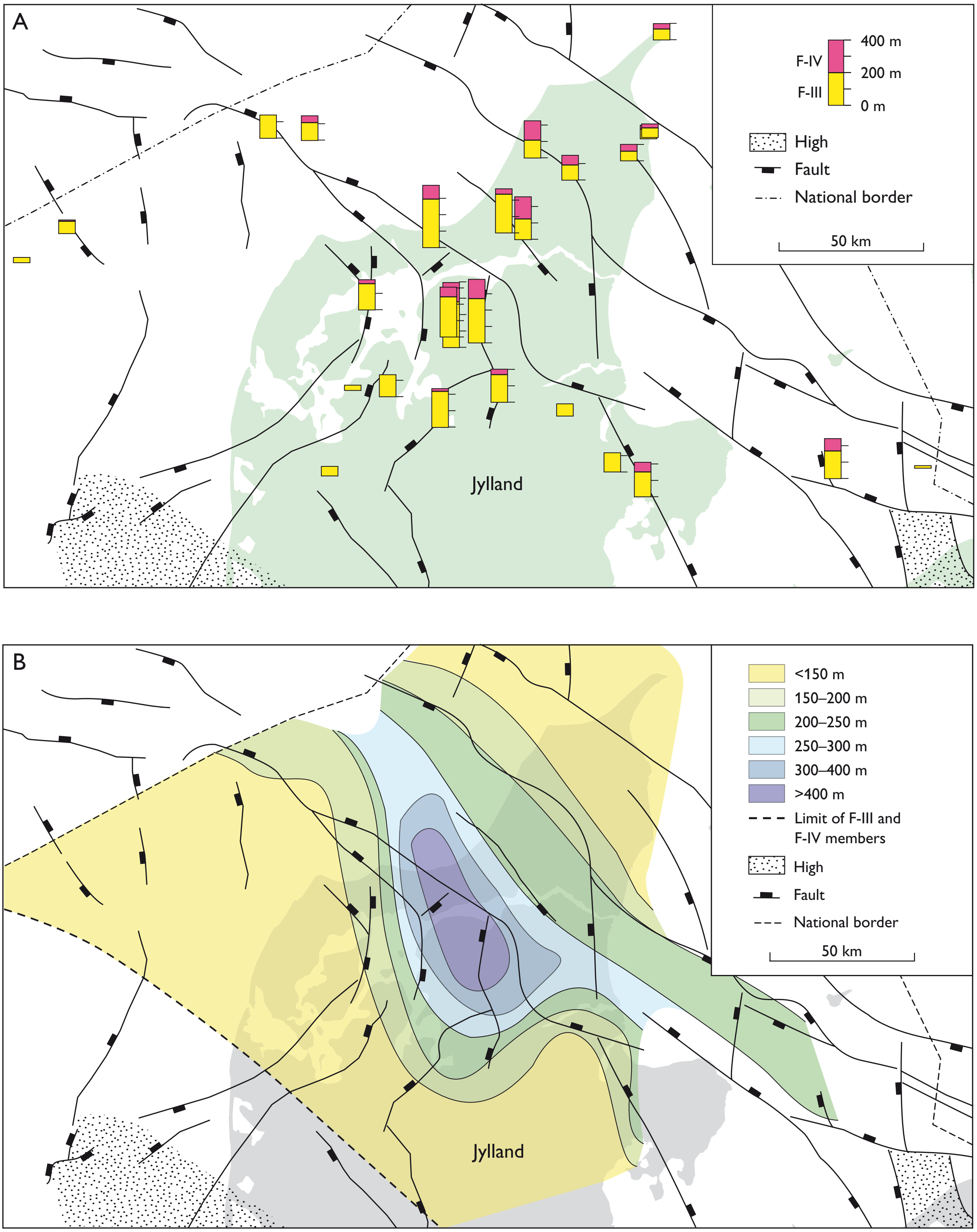


Fig. 25. **A**: Thickness of the Lower Jurassic lithostratigraphic F-III and F-IV members in the Fjerritslev Formation in the studied wells; the base of each schematic stratigraphic column is located at the well site. **B**: Isopach map of the combined thickness of the F-III and F-IV members. The largest thicknesses occur in the Himmerland Graben.

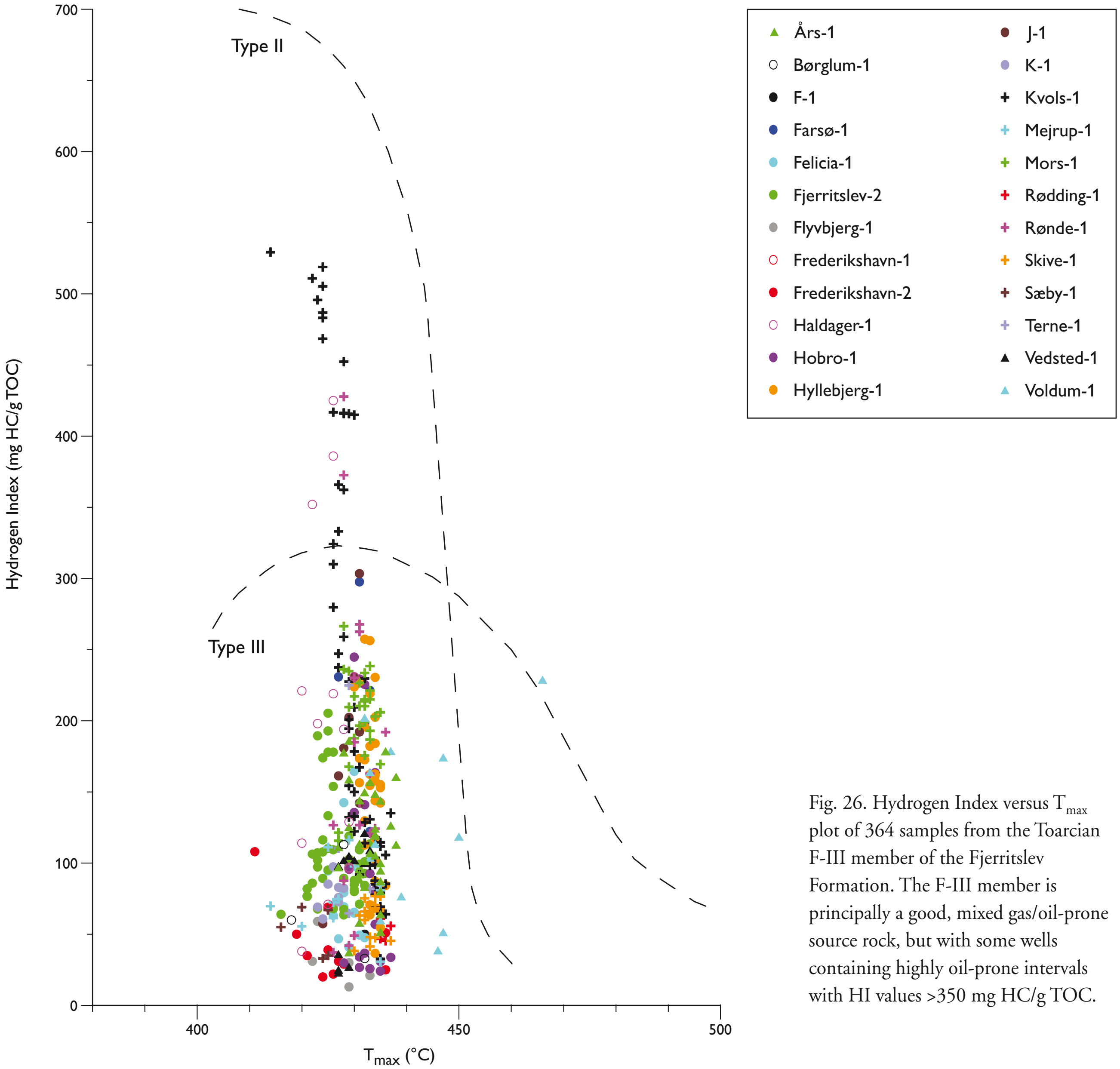


Fig. 26. Hydrogen Index versus T_{max} plot of 364 samples from the Toarcian F-III member of the Fjerritslev Formation. The F-III member is principally a good, mixed gas/oil-prone source rock, but with some wells containing highly oil-prone intervals with HI values >350 mg HC/g TOC.

A marginal gas generation potential is shown by the member in the J-1 well (Fig. 30B), where the average HI value is only 130 mg HC/g TOC and the maximum HI value is 178 mg HC/g TOC.

The average HI values in the F-III and F-IV members, calculated from the entire thickness of the members, classify the majority of well-sections as gas-prone and a few as gas-/oil-prone (Fig. 34). The source-rock quality of the F-III and F-IV members, as shown above, varies considerably between wells and within the members in individual wells; average values thus mask specific oil-prone intervals. To illustrate further the evaluation of the source rocks in the F-III and F-IV members, a 'net quality map' was constructed showing the cumulative thickness of intervals with HI values >200 mg HC/g TOC (Fig. 35A; Table 2) and the net/gross ratio (cumulative thickness/total thickness of F-III + F-IV members). The map thus displays the occurrence and thickness of source rocks with a mixed gas/oil or oil generation potential and suggests that the thickest cumulative source-rock section with HI >200 mg HC/g TOC occurs in the basin centre (Kvols-1, Mors-1 and Rønde-1 wells), where the best source-rock quality also occurs. The Kvols-1 and Rønde-1 wells contain about 80–90 m net oil-prone source rock with average HI values of 369 and 404 mg HC/g TOC, respectively. It is also notable that the Haldager-1 well in the Sorgenfrei–Tornquist Zone contains *c.* 40 m net source rock with an average HI of 294 mg HC/g TOC. The thinner net source-rock thicknesses

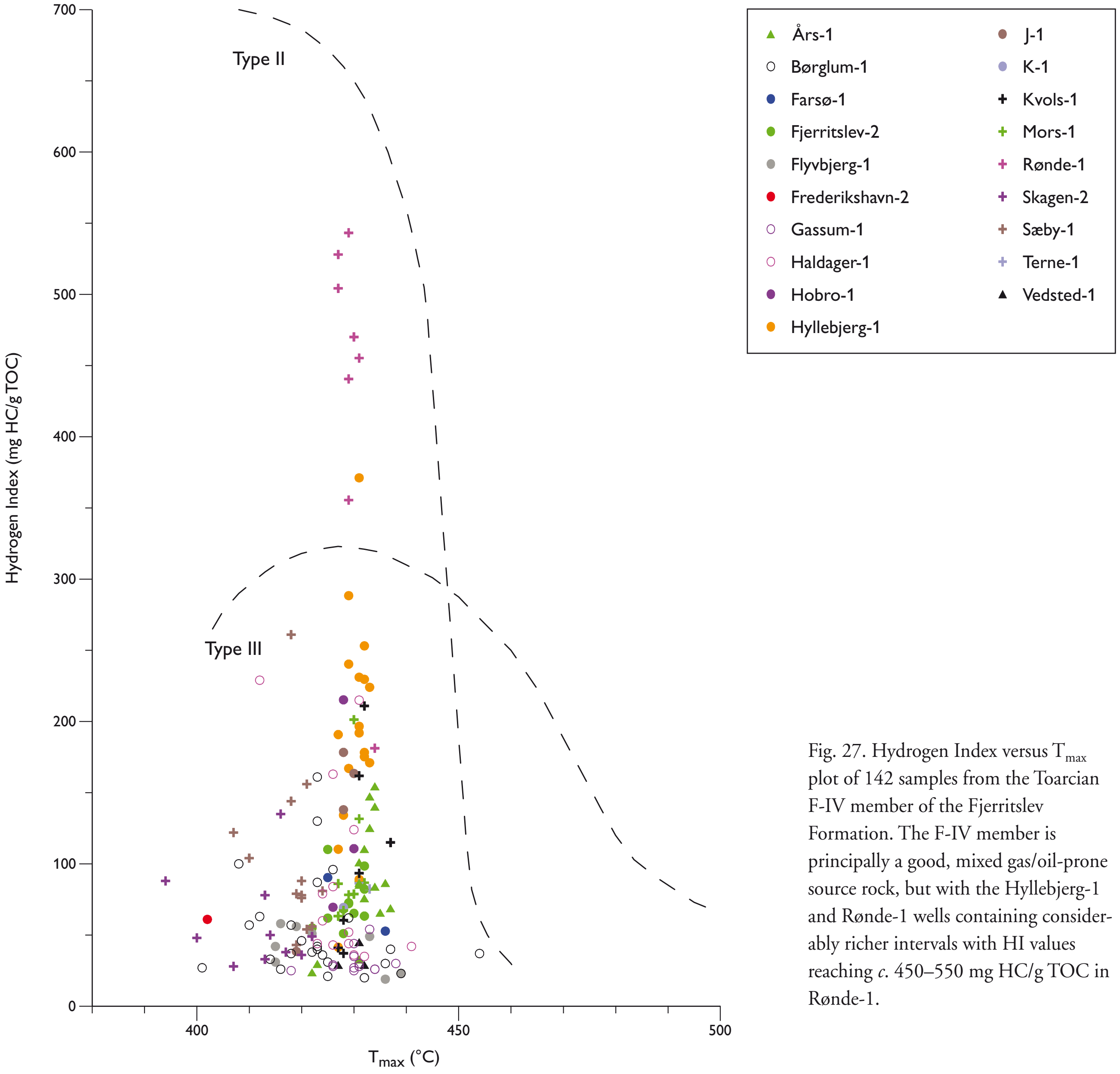


Fig. 27. Hydrogen Index versus T_{max} plot of 142 samples from the Toarcian F-IV member of the Fjerritslev Formation. The F-IV member is principally a good, mixed gas/oil-prone source rock, but with the Hyllebjerg-1 and Rønde-1 wells containing considerably richer intervals with HI values reaching *c.* 450–550 mg HC/g TOC in Rønde-1.

in the Hobro-1, Hyllebjerg-1 and Voldum-1 wells, which are also situated centrally in the basin, may partly be explained by erosion of the upper part of the F-IV member during the Middle Jurassic uplift event. In other centrally placed wells, such as Mejrup-1, Rødding-1 and Skive-1, the entire F-IV member and most of the F-III member have been eroded, resulting in potential source rocks being thin or absent in these areas.

The limiting factor for the petroleum potential of the study area is the thermal maturity of the richest source-rock units, the F-III and F-IV members. It has been shown that the depth to the top of the oil window, corresponding to a VR of 0.6%R_o, is about 3050–3100 m (Figs 20A, 22A). Using this threshold, the F-III and F-IV members are thermally immature in the investigated wells, also demonstrated by the T_{max} values (Fig. 35B). The largest discrepancy between T_{max} and VR values is observed in the Terne-1 well, which compared to the other wells also yields unusually low VR values (Figs 18, 19, 21). The notable lack of hydrocarbon shows in the wells drilled in the study area, including the central deep part, supports the suggestion that the F-III and F-IV source rocks had not, prior to post-Early Cretaceous uplift, been buried to the necessary depth for petroleum generation to occur. The Mors-1 and Års-1 wells represent locations where the Fjerritslev Formation has been buried below the depth of the top of the oil window, but in both wells the petroleum generation potential of the sediments is relatively poor to non-existent.

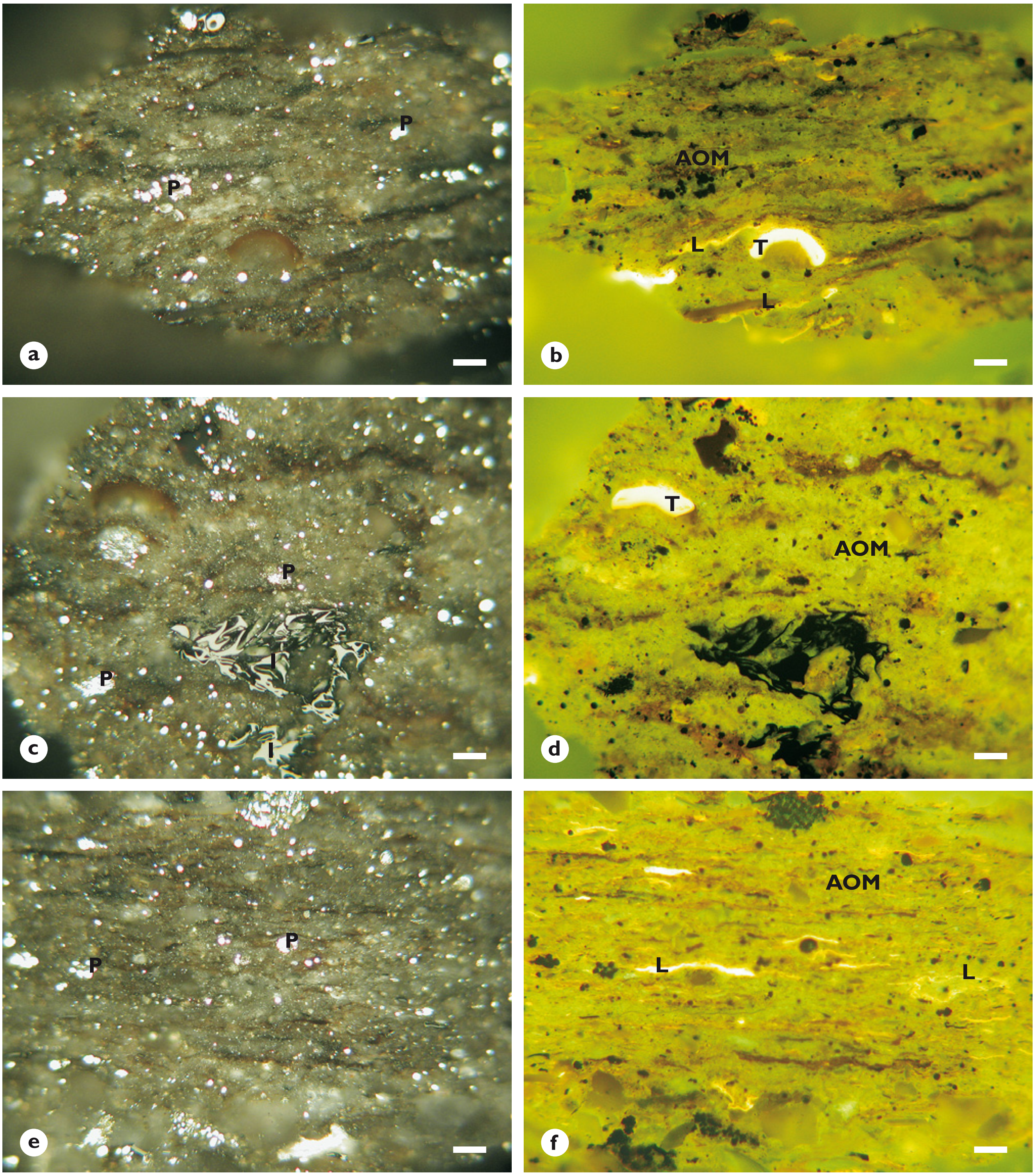


Fig. 28. Paired photomicrographs (reflected light, oil immersion; scale bar is *c.* 30 µm) of the organic material in the oil-prone F-III member in the Kvols-1 well; left (a, c, e): white light; right (b, d, f): fluorescence-inducing blue light. **a-d**: Fluorescing, amorphous organic matter (**AOM**; probably algal-derived) and alginite with *Tasmanites* (**T**) and *Leiosphaeridia* (**L**) morphology in cuttings from *c.* 1996 m. Inertinite (**I**) and framboidal pyrite (**P**) are also present. TOC = 2.56 wt%, HI = 416 mg HC/g TOC. **e, f**: Fluorescing AOM (probably algal-derived) and several alginites with *Leiosphaeridia* (**L**) morphology in cuttings from *c.* 2012 m. Abundant framboidal pyrite (**P**) present. TOC = 3.57 wt%, HI = 487 mg HC/g TOC.

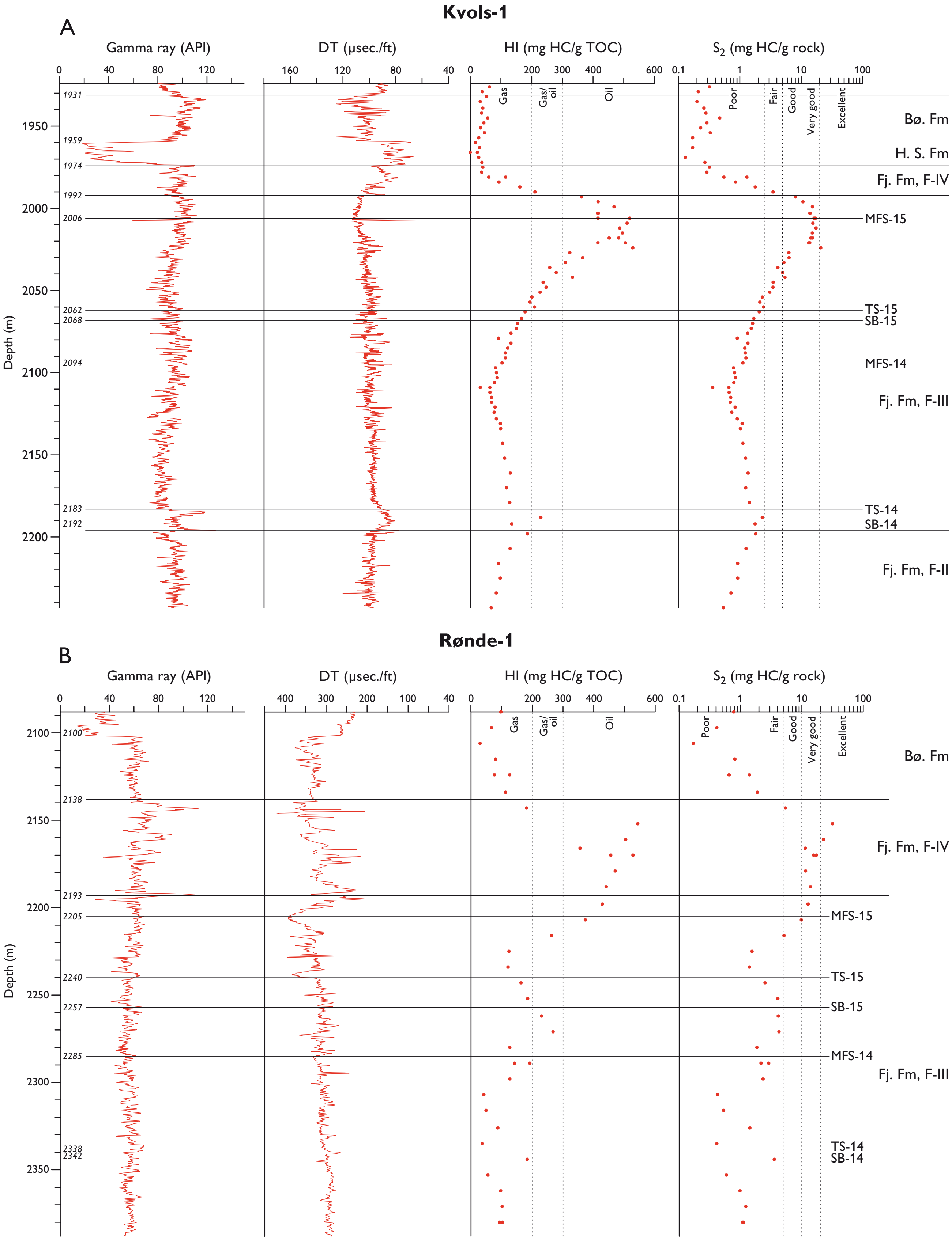


Fig. 29. Plots showing well logs, Hydrogen Index (**HI**) values, S_2 yields, sequence stratigraphic key surfaces and formations in the Kvols-1 (**A**) and Rønde-1 (**B**) wells. Note the oil-prone upper part of the F-III member in Kvols-1 and the oil-prone F-IV member in Rønde-1. **DT**, sonic velocity; **MFS**, maximum marine flooding surface; **SB**, sequence boundary; **TS**, transgressive surface. **Bø.**, Børglum; **Fj.**, Fjerritslev; **H.S.**, Haldager Sand.

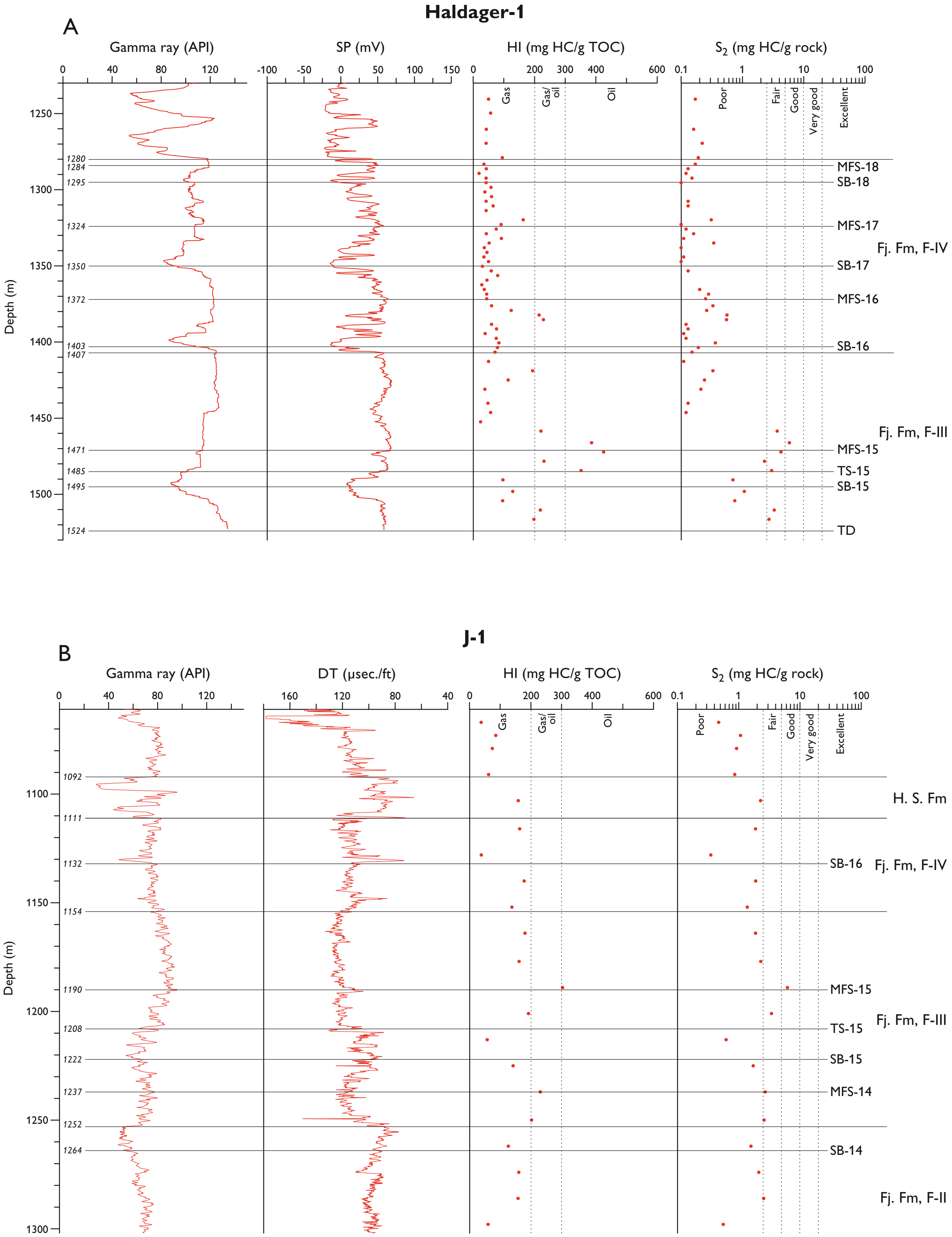


Fig. 30. Plots showing well logs, Hydrogen Index (**HI**) values, S_2 yields, sequence stratigraphic key surfaces and formations in the Haldager-1 (**A**) and J-1 (**B**) wells. Note the oil-prone interval in the F-III member in Haldager-1. **DT**, sonic velocity; **SP**, self-potential; **TD**, total depth. For further abbreviations, see Fig. 29.

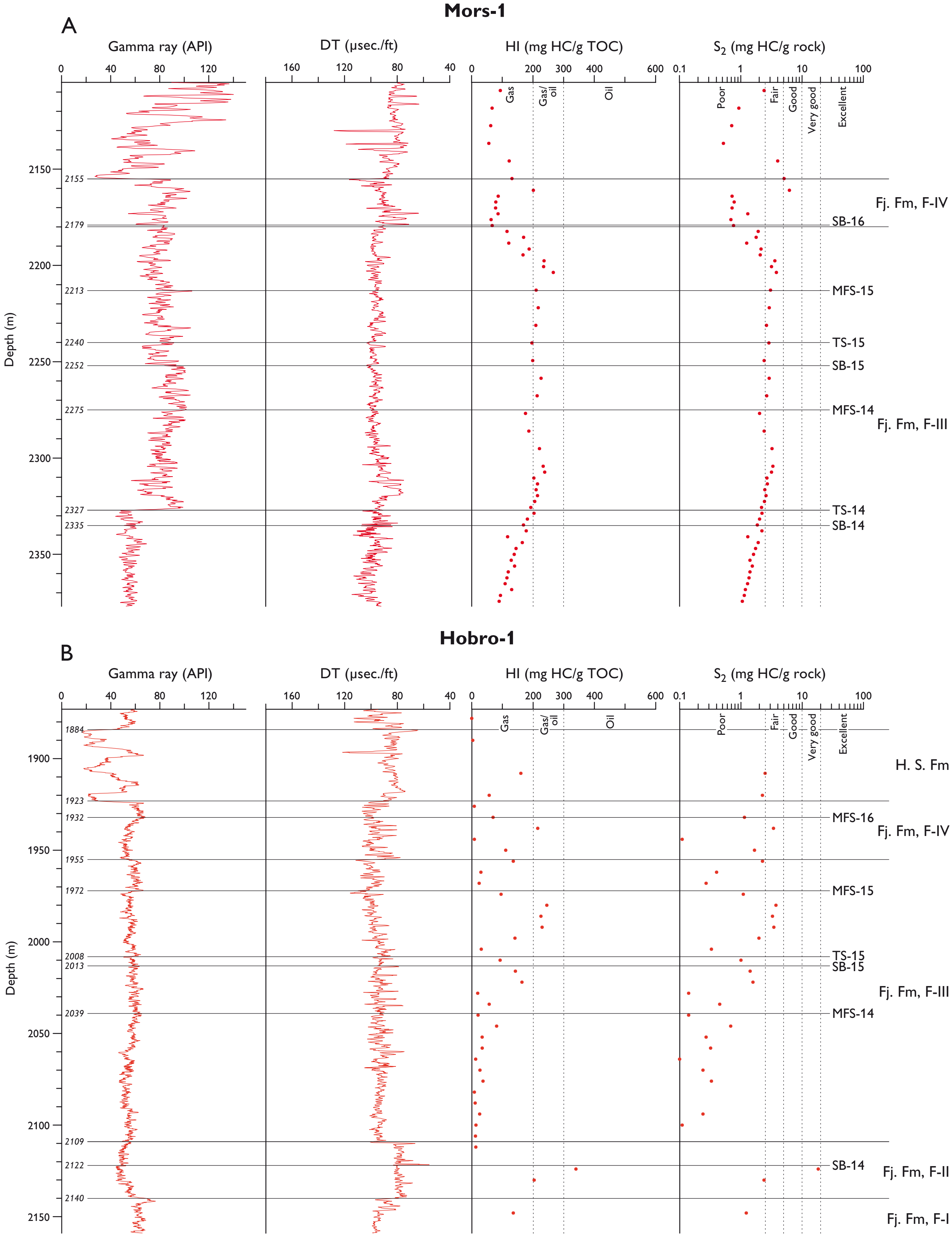


Fig. 31. Plots showing well logs, Hydrogen Index (**HI**) values, S_2 yields, sequence stratigraphic key surfaces and formations in the Mors-1 (**A**) and Hobro-1 (**B**) wells. Note the *c.* 125 m thick interval in the F-III member in Mors-1 in which HI values exceed 200 mg HC/g TOC. **DT**, sonic velocity. For further abbreviations, see Fig. 29.

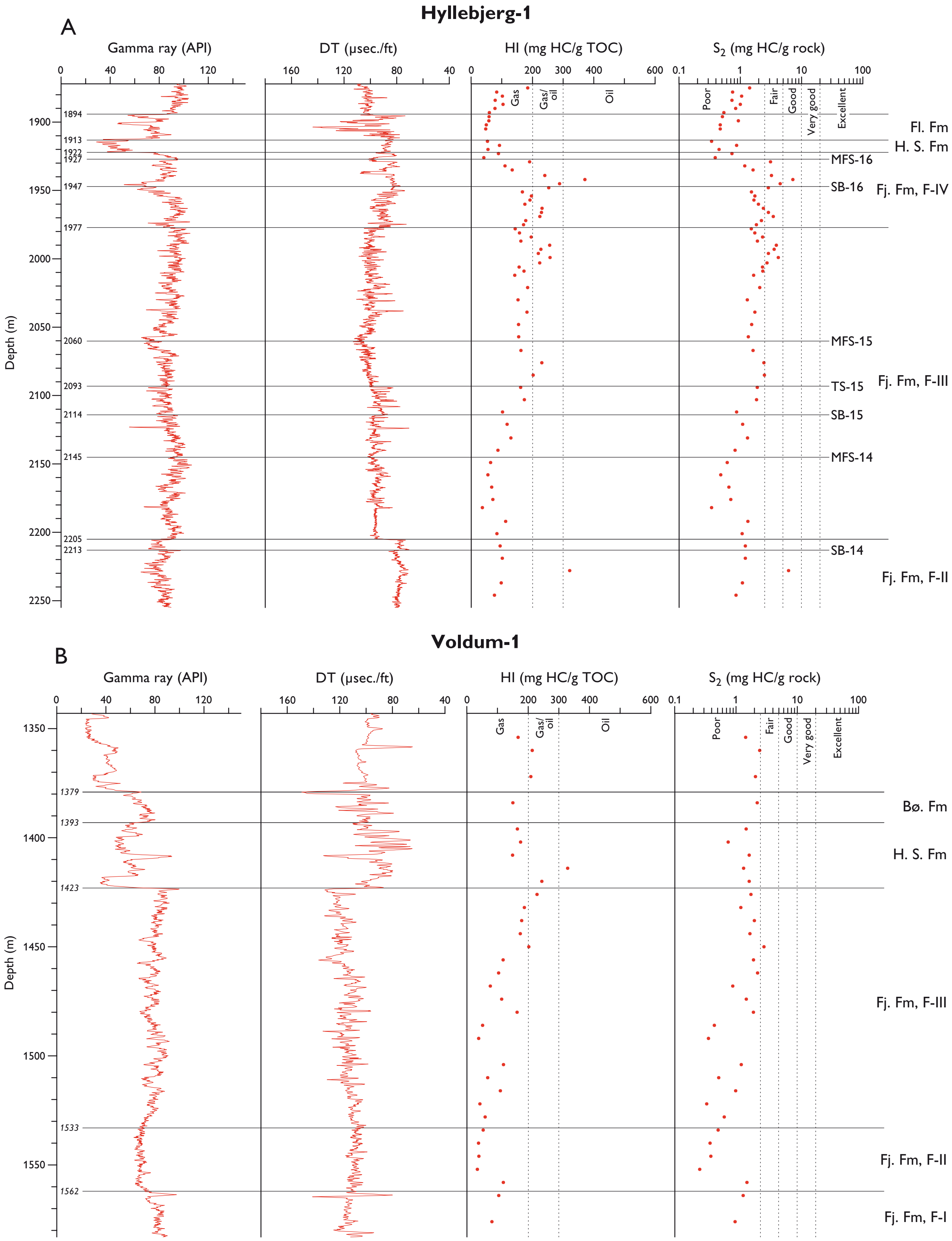


Fig. 32. Plots showing well logs, Hydrogen Index (**HI**) values, S_2 yields, sequence stratigraphic key surfaces and formations in the Hyllebjerg-1 (**A**) and Voldum-1 (**B**) wells. In Hyllebjerg-1, note the increased HI values in the upper part of the F-III member and in the middle part of the F-IV member. **DT**, sonic velocity. For further abbreviations, see Fig. 29.

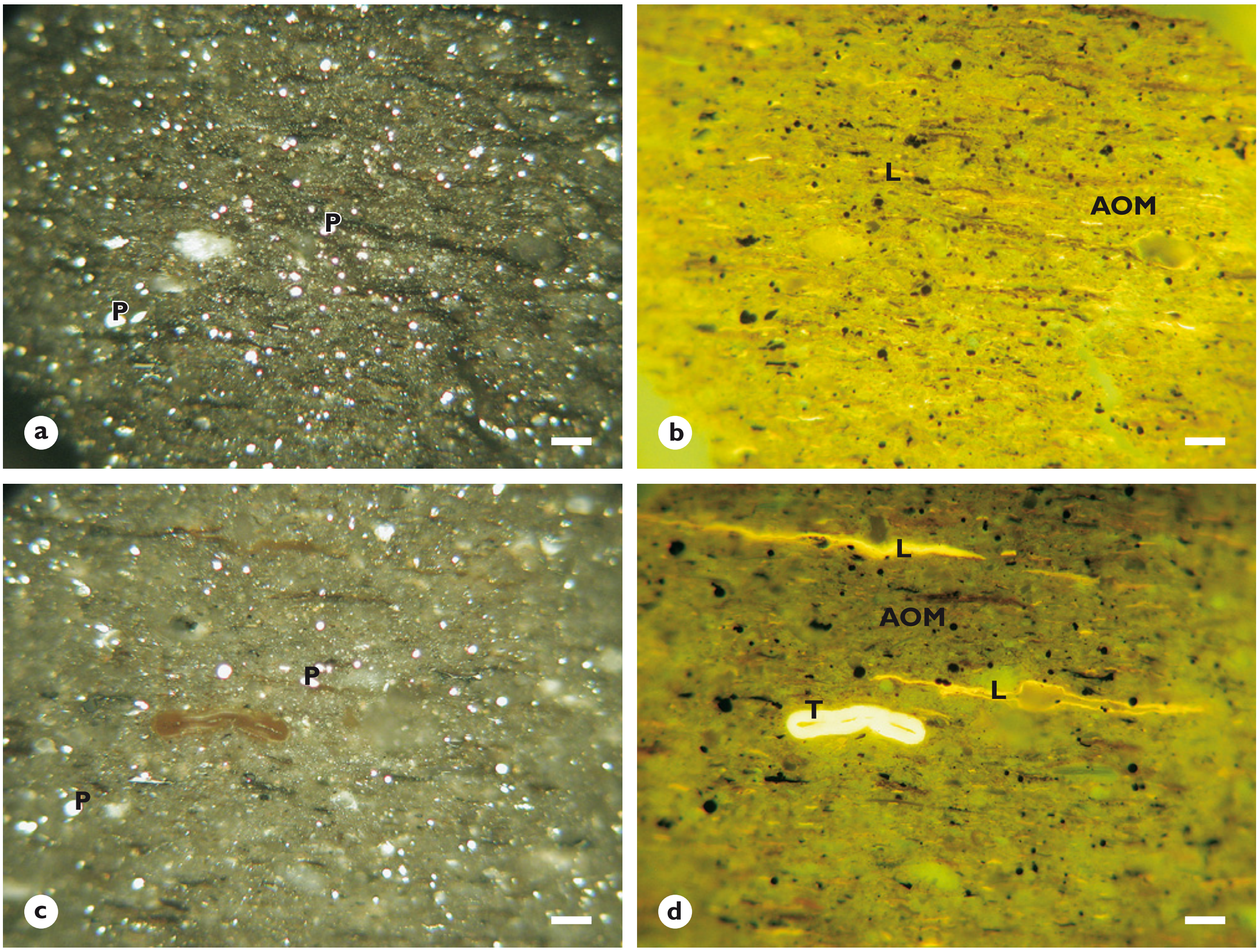


Fig. 33. Paired photomicrographs (reflected light, oil immersion; scale bar is *c.* 30 µm) of the organic material in cuttings sample (*c.* 2152 m) from the oil-prone F-IV member in the Rønde-1 well; left (a, c): white light; right (b, d): fluorescence-inducing blue light. The cuttings contain an abundance of fluorescing, amorphous organic matter (**AOM**) and detrital liptinite (probably algal-derived) together with *Leiosphaeridia* (**L**) and *Tasmanites* (**T**) alginite. **P**, framboidal pyrite. TOC = 5.81 wt%, HI = 543 mg HC/g TOC.

Middle Jurassic units

In the Yme Field in the Egersund Basin, where the Bryne Formation (equivalent to the Haldager Sand Formation) is thickly developed, the formation contains shales that show a good to excellent oil generation potential with TOC values of 2–13 wt% and HI values of 100–480 mg HC/g TOC. Coal seams within the Middle Jurassic – lower Upper Jurassic of this field are also oil-prone in places, with HI values exceeding 400 mg HC/g TOC. Similarly, Middle Jurassic coals and carbonaceous lacustrine–brackish shales of the Lulu Formation are considered to have sourced the oil and gas/condensate accumulations in the Lulita and Harald Fields in the Søgne Basin of the North Sea. In this area, the type of generated petroleum is considered to have been controlled by lateral coal facies variations related to the proximity of peat formation to the coeval coastline (Petersen *et al.* 1998, 2000; Petersen & Brekke 2001). Coals formed in the coastal reaches of the mires are more oil-prone than their more landward equivalents.

In the study area, the Middle Jurassic Haldager Sand Formation is dominated by fluvial, estuarine and shallow marine sandstones interbedded with marine and lacustrine mudstones and thin coal seams (Nielsen 2003). The generation potential of the formation is low, with only a few exceptions. In the Haldager-1 well, two samples from a 4–5 m thick marine mudstone have high HI values (342 and 637 mg HC/g TOC), and the Terne-1 well shows HI values of 260 mg HC/g TOC. Both wells are situated in the Sorgenfrei–Tornquist Zone where the Middle Jurassic is thickest.

There may thus be a relationship between the gross thickness of the Middle Jurassic succession, the palaeo-

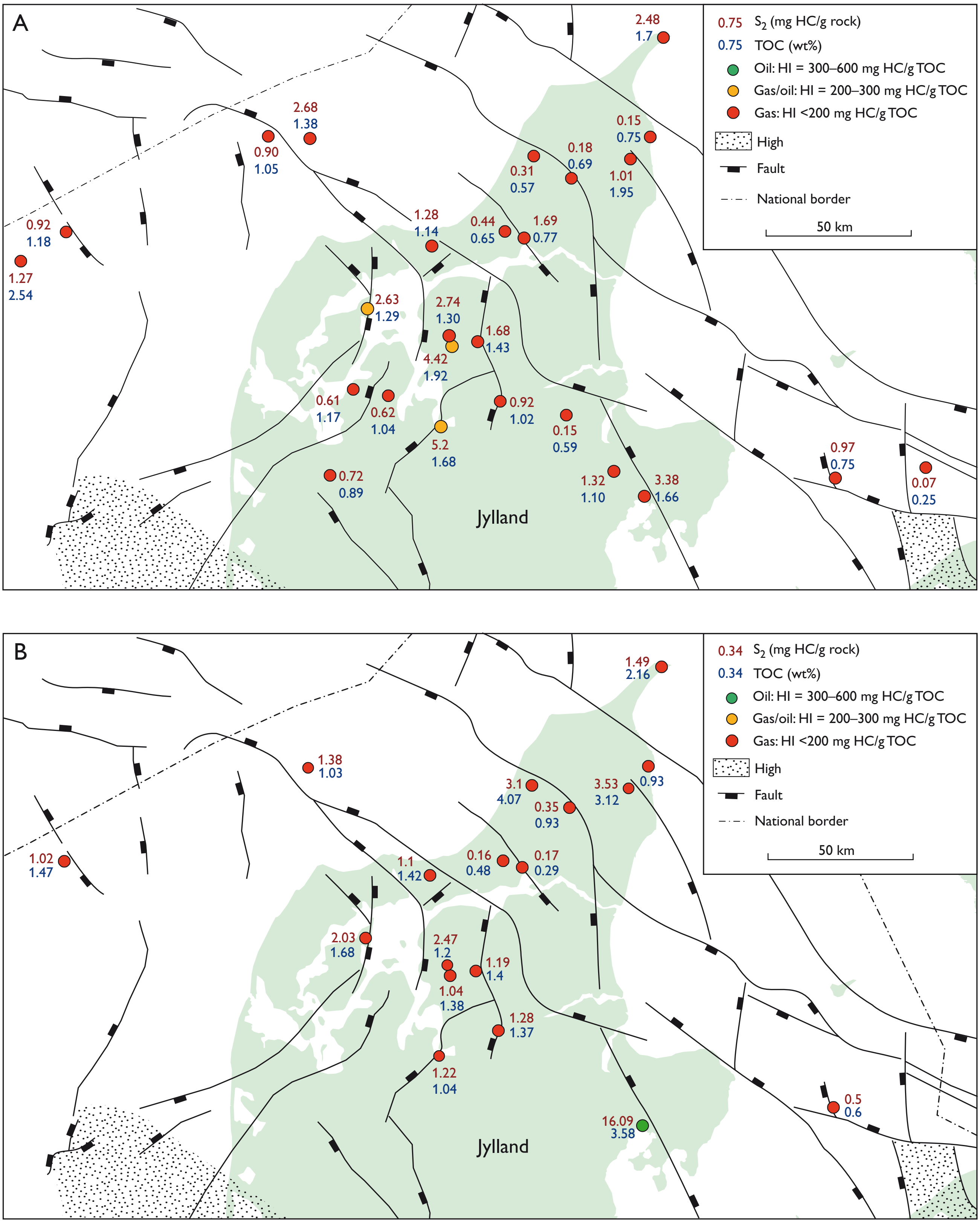


Fig. 34. The average source-rock quality of the Lower Jurassic F-III member (**A**) and F-IV member (**B**) of the Fjerritslev Formation.

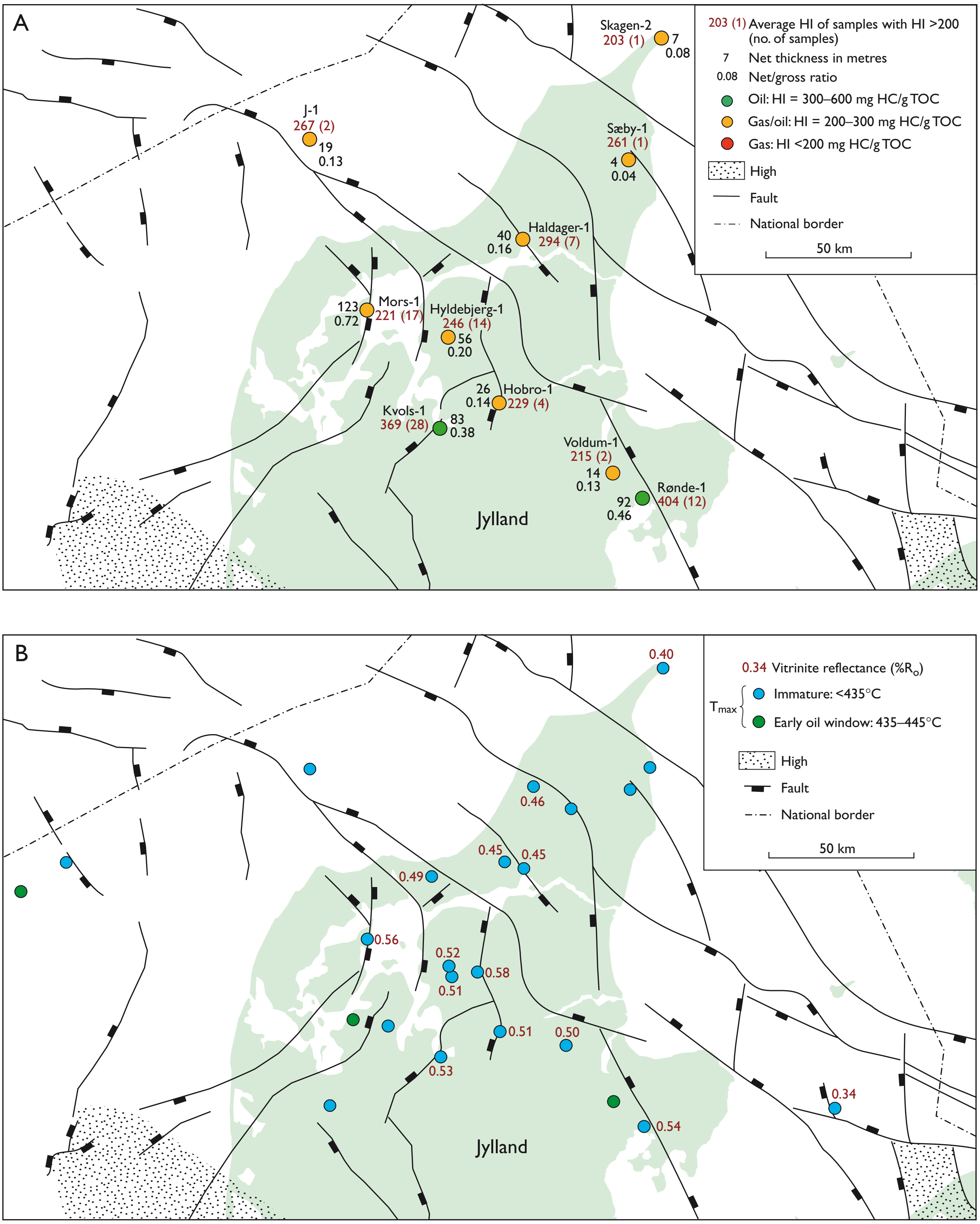


Fig. 35. **A**: Cumulative net source-rock thickness of the intervals in the F-III and F-IV members with HI values exceeding 200 mg HC/g TOC, i.e. a source rock with a mixed gas/oil or oil generation potential. **B**: Thermal maturity of the F-III and F-IV members of the Fjerritslev Formation. Vitrinite reflectance and T_{max} values indicate immaturity with regard to petroleum generation.

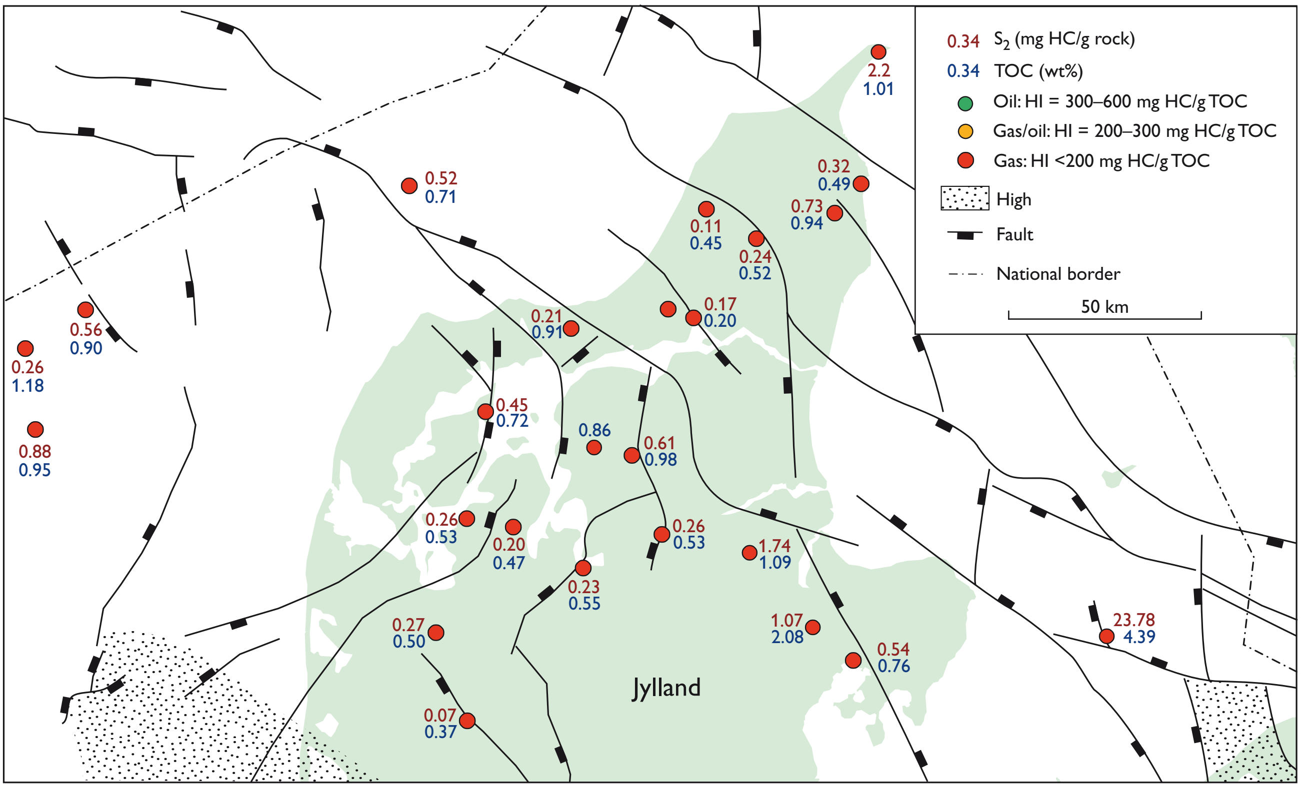


Fig. 36. Average source-rock quality of the entire uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation.

geographic position and the occurrence of shales and coals with an oil generation potential. Oil-prone coals in the Middle Jurassic may be best developed in areas with most pronounced subsidence and hence relatively large rates of formation of accommodation space during deposition.

Upper Jurassic – Lower Cretaceous units

In most wells, the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation is dominated by shallow marine and paralic siltstones and sandstones (Michelsen *et al.* 2003) with no petroleum generation potential. The average HI of the entire Frederikshavn Formation indicates a gas-prone source potential (Fig. 36), but the formation contains intervals with good to excellent oil generation potential, as demonstrated by the Gassum-1, Hyllebjerg-1, Skagen-2, Sæby-1, Terne-1 and Voldum-1 wells (Figs 37, 38A; Table 3). The section in Terne-1 is particularly noteworthy, with HI values >1100 mg HC/g TOC, although these values in part reflect contamination by gel mud and cement applied during drilling. Nevertheless, solvent-extracted samples are still encouraging, with a cumulative net source-rock unit of *c.* 150 m containing on average 5.7 wt% TOC and HI values of the extracted samples reaching 580 mg HC/g TOC, averaging 478 mg HC/g TOC (Fig. 38A; Table 3). Microscopical kerogen analyses show an abundance of amorphous algal organic matter in the form of filamentous lamalginite and alginite with morphology similar to the extant fresh to brackish water *Botryococcus* algae (Type I kerogen; Fig. 39). Brackish, oxygen-deficient conditions during deposition are suggested by the abundance of framboidal pyrite associated with the organic matter (Fig. 39). The probable lacustrine origin of these deposits in Terne-1 suggests a local development, as the formation is typically of shallow marine to offshore origin (Michelsen *et al.* 2003).

The Skagen-2 well contains a *c.* 78 m thick net source-rock interval with an average HI value of 241 mg HC/g

Table 3. Net source-rock (SR) thicknesses, Frederikshavn Fm

Well	Net SR (m)	Gross (m)	Net/ gross	Average HI*, Net SR interval (number of samples)
Gassum-1	17	101	0.17	320 (3)
Hyllebjerg-1	29	146	0.20	243 (4)
Skagen-2	78	176	0.44	241 (7)
Sæby-1	10	105	0.10	329 (1)
Terne-1	150	258	0.58	478 (10)
Voldum-1	26	66	0.39	257 (3)

* Average HI in Net SR intervals based on HI values ≥200 mg HC/g TOC

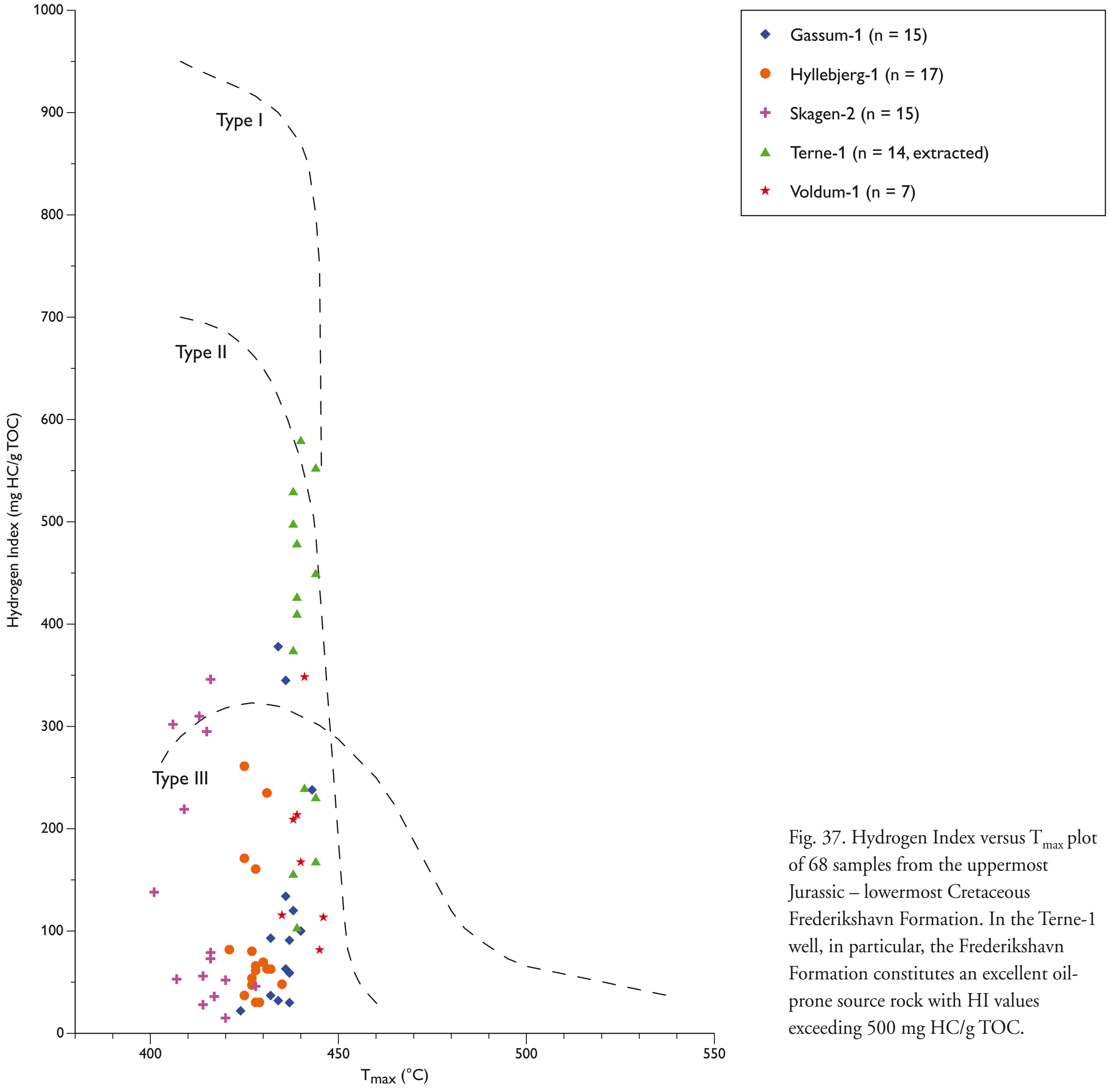


Fig. 37. Hydrogen Index versus T_{max} plot of 68 samples from the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation. In the Terne-1 well, in particular, the Frederikshavn Formation constitutes an excellent oil-prone source rock with HI values exceeding 500 mg HC/g TOC.

TOC and a maximum value close to 350 (Fig. 38A). In the Gassum-1 well, most HI values are low but a few samples yield HI values >300 mg HC/g TOC (Fig. 38A); these high values are abnormal compared to the general trend and may reflect thin layers with higher quality kerogen in an otherwise sand-dominated succession. The Hyllebjerg-1 well has a *c.* 29 m thick net source-rock section with an average HI value of 243 mg HC/g TOC, whereas the average HI value of *c.* 26 m net source rock in the Voldum-1 well is 257 mg HC/g TOC (Fig. 38A; Table 3).

The Frederikshavn Formation thus locally contains good to excellent oil source rocks in the study area. Towards the west in the Egersund Basin, the broadly time-equivalent Tau Formation is known as the principal source for oil, and in the North Sea the uppermost Jurassic – lowermost Cretaceous marine shales of the Farsund Formation and equivalents (Kimmeridge Clay, Mandal and Draupne formations) are well known as the primary oil source rocks (e.g. Ineson *et al.* 2003). As for the Lower Jurassic Fjerritslev Formation, the major problem in the Danish area is to find areas where the Frederikshavn succession is sufficiently buried to be thermally mature with regard to petroleum generation. VR values from 0.36–0.53% R_o and the majority of T_{max} values <430–435°C indicate that the potential source rocks are thermally immature (Fig. 38B).

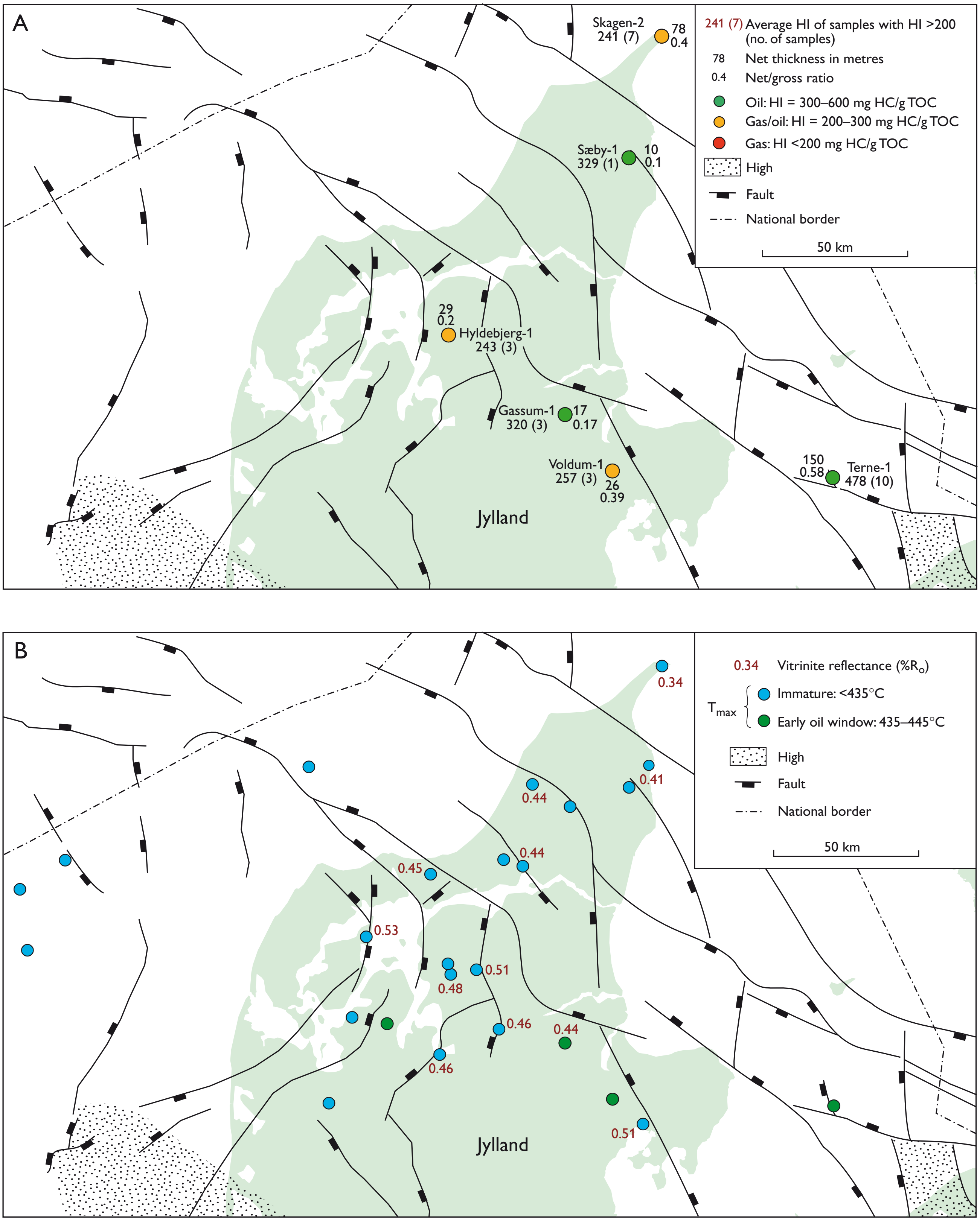


Fig. 38. **A**: Cumulative net source-rock thickness of the intervals in the Frederikshavn Formation with HI values exceeding 200 mg HC/g TOC, i.e. a source rock with a mixed gas/oil or oil generation potential. **B**: Thermal maturity of the Frederikshavn Formation. Vitrinite reflectance values indicate immaturity, whereas T_{max} values may suggest early oil window maturity in four wells located in the central part of the basin or in the Sorgenfrei–Tornquist Zone.

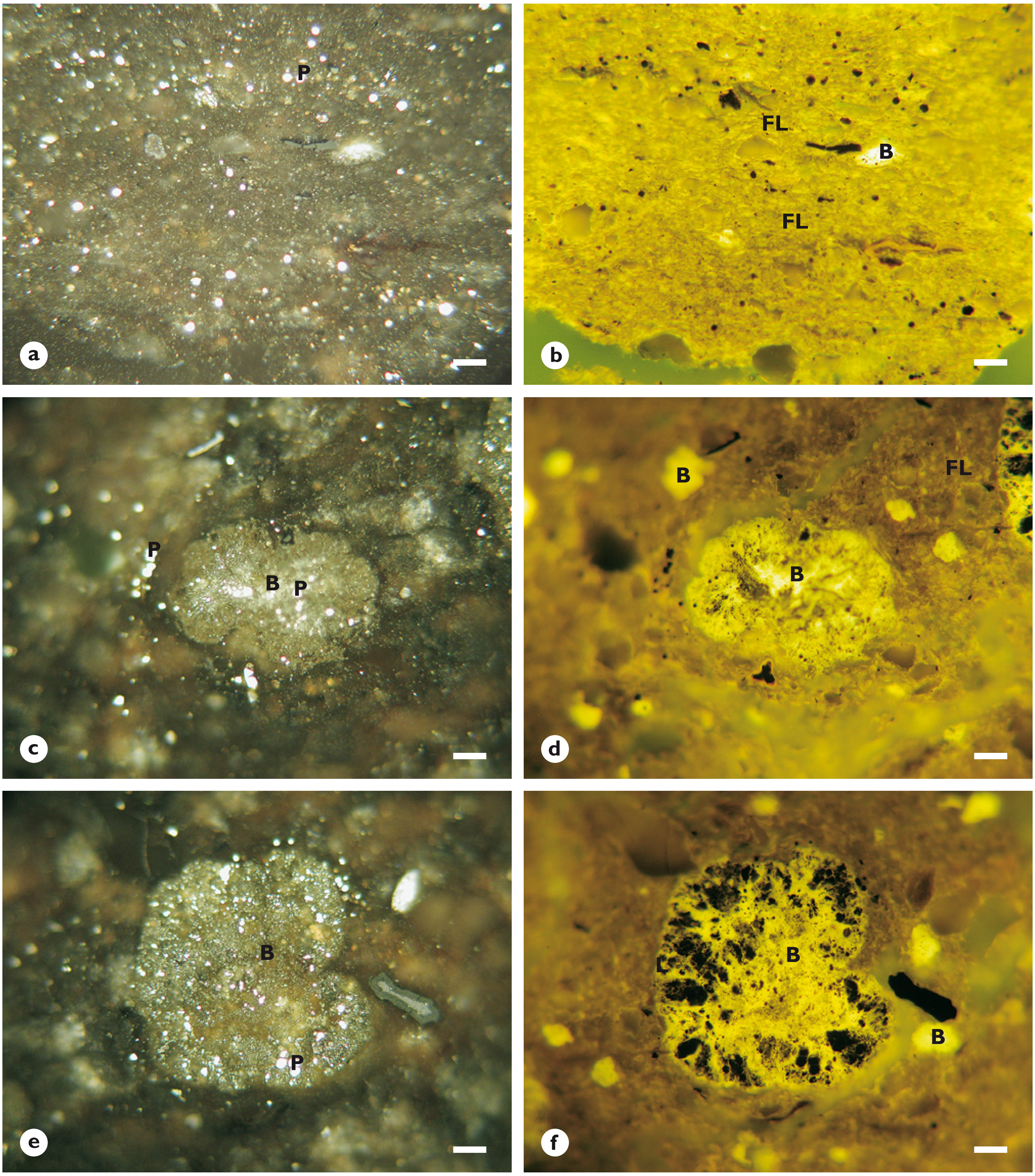


Fig. 39. Paired photomicrographs (reflected light, oil immersion; scale bar is *c.* 30 µm) of the organic material in the oil-prone lacustrine Frederikshavn Formation in the Terne-1 well; left (a, c, e) white light; right (b, d, f): fluorescence-inducing blue light. **a-f**: Abundance of fluorescing, filamentous lamalginite (**FL**) and *Botryococcus*-type alginites (**B**) of varying size in cuttings from *c.* 200–210 m. Abundant framboidal pyrite (**P**) has been formed within the large *Botryococcus*-type alginite bodies. TOC = 7.30 wt%, $HI_{extracted}$ = 498 mg HC/g TOC.

Lower Cretaceous units

In general, the Lower Cretaceous succession of the study area contains few and relatively thin potential oil source rocks. Three wells, the Lavø-1, Sæby-1 and Års-1, contain intervals in the Lower Cretaceous (Vedsted Formation or undifferentiated Lower Cretaceous) with a petroleum generation potential. In the Sæby-1 well, a *c.* 20 m thick organic-rich interval has TOC contents up to 5.28 wt% and HI values from 320–472 mg HC/g TOC, averaging 388 mg HC/g TOC; the interval is thus an excellent potential oil and gas source rock. Similarly, a *c.* 20 m thick interval in the Års-1 well possesses a mixed oil/gas generation potential, although the potential is poorer than in Sæby-1 as the HI values range from 210–411 mg HC/g TOC, averaging 294 mg HC/g TOC. In the Lavø-1 well, a *c.*18 m thick potential source-rock interval with HI values from 175–242 mg HC/g TOC is present. The Lower Cretaceous is, however, thermally immature in all well sections.

Potential reservoirs

The principal sedimentary units of interest with respect to potential reservoirs in the Norwegian–Danish Basin are the sandstones of the Upper Triassic – lowermost Jurassic Gassum Formation and the Middle Jurassic Haldager Sand Formation. The growth of salt pillows caused local topographic relief that influenced the deposition of these two reservoir units, as well as the intervening Fjerritslev Formation. The units thicken into rim synclines as indicated, for example, by the Felicia-1/1A section, and may thin considerably over salt pillows. These principal potential reservoirs are reviewed below with respect to their gross distribution, thickness development and properties.

A number of secondary potential reservoir units are also known from the Norwegian–Danish Basin and the Fennoscandian Border Zone, including the Lower Triassic Bunter Sandstone, the Lower–Upper Triassic Skagerrak Formation, the Lower Jurassic F-II member of the Fjerritslev Formation, the Upper Jurassic Flyvbjerg Formation and the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation. These secondary reservoir units are briefly described after the principal reservoirs.

Gassum reservoir

Shoreface and fluvial–estuarine sandstones interbedded with marine mudstones, lagoonal heteroliths and mudstones, lacustrine mudstones and thin coal seams occur in the Gassum Formation (Nielsen 2003). In the Himmerland Graben, the Sorgenfrei–Tornquist Zone and the Skagerrak –Kattegat Platform, sandstones are commonly the dominant lithology, and petrophysical log evaluations typically show net-to-gross ratios of 0.3–0.7 and porosities of 15–25%. The formation is more sand-poor in the central part of the basin with net-to-gross ratios of 0.1–0.2 (e.g. Mejrup-1, Nøvling-1, Vemb-1, Vinding-1). The sandstones are predominantly well to moderately sorted, fine- to medium-grained, locally coarse-grained and slightly pebbly. The shoreface sandstones occur as widespread sheets, 4–30 m thick, separated by marine transgressive mudstones and lagoonal heteroliths. Thick fluvial–estuarine sandstones mostly overlie the major SB 5 sequence boundary (Figs 10, 12; Nielsen 2003).

The formation is 50–150 m thick in central parts of the Norwegian–Danish Basin, its thickness being influenced by proximity to salt structures and faults. The formation thickens to 170–200 m in the fault-bounded Himmerland Graben and the northern part of the Sorgenfrei–Tornquist Zone. It thickens further to more than 300 m in the southern part of the fault zone where deposition of sand continued from the Triassic until the Early Sinemurian (Nielsen 2003). The thickness ranges from 69–205 m in the F-1, K-1, Felicia-1/1A and J-1 wells (Fig. 1). The large thickness (205 m) of the formation in Felicia-1/1A, with thick mudstones in the middle part of the formation, probably reflects an excess of accommodation space in the rim syncline associated with the nearby large salt pillow. The thickness decreases to 10–80 m on the Skagerrak–Kattegat Platform.

It is generally assumed that the siliciclastic material was mainly supplied from the Baltic Shield to the north and east. However, the dominance of mineralogically mature and better sorted sandstones in the Stenlille area and in the Ullerslev-1 well suggests that sand may have been supplied from the erosion of older sediments, such as the Triassic Bunter Sandstone on the Ringkøbing–Fyn High (Larsen 1966; Nielsen 2003).

The Gassum Formation is utilised in geothermal energy installations onshore Denmark at a depth of *c.* 1200 m (Thisted, northern Jylland) and is used for storage of natural gas in a structure at *c.* 1550 m depth in the eastern part of the basin (Stenlille area; Fig. 1).

Haldager Sand reservoir

The Haldager Sand Formation consists primarily of sandstones interbedded with thin mudstones. The sandstones are medium- to coarse-grained, slightly pebbly, commonly well to moderately sorted but locally poorly sorted. Sandstones are the dominant lithology, and petrophysical log evaluations typically show net-to-gross ratios of 0.4–0.8 and porosities of 15–30%. In the Sorgenfrei–Tornquist Zone, where subsidence continued despite regional uplift, the formation consists of four thick fluvial–estuarine to shallow marine sandstone units separated by marine and lagoonal–lacustrine mudstones (Nielsen 2003). Beyond the fault-bounded graben, in areas that experienced uplift in the early part of the Middle Jurassic, sandstones were mainly deposited by braided rivers, and the sand bodies are expected to be laterally coherent without significant primary hydraulic barriers. Anomalies with respect to facies and thickness occur locally in rim synclines associated with salt structures.

The distribution and thickness of the Haldager Sand reservoir are strongly influenced by regional syndepositional tectonism, local faulting and salt structures. Sediments were supplied from the north and east, but deep erosion of Triassic and older strata on the Ringkøbing–Fyn High and Lower Jurassic mudstones along the northern flank of the high added a substantial amount of material. As a result of the uplift of the Ringkøbing–Fyn High, high-energy braided rivers shed erosion products into the Sorgenfrei–Tornquist Zone, which experienced slow fault-controlled subsidence. Between the Fjerritslev and Børglum Faults, the formation attains a thickness of 30–175 m. Outside the Sorgenfrei–Tornquist Zone, the thickness and number of sandstone units decreases. On the Skagerrak –Kattegat Platform, the formation is 15–50 m thick and in the central part of the basin it is 25–50 m thick. In the southern and south-western part of the study area, the formation is thin and has a patchy distribution with thicknesses below 10 m.

Additional reservoirs

The Lower Triassic Bunter Sandstone and the Lower–Upper Triassic Skagerrak Formations constitute additional potential reservoir units in the study area. The Bunter Sandstone Formation consists of orange, red-brown and yellow-brown, medium- to fine-grained, moderately to well-sorted, cemented sandstones deposited mainly in braided ephemeral rivers and by eolian dunes. The Skagerrak Formation consists of interbedded sandstones, siltstones, claystones and anhydrites. The sandstones are arkosic, grey, red, orange-brown, fine- to coarse-grained, poorly sorted, angular–subangular and partly cemented, and were deposited on alluvial fans or braided river plains. Both formations are dominated by sandstones and potential internal barriers or seals are rare.

Another potential reservoir unit is represented by a muddy sandstone unit, 20–30 m thick, in the upper part of the Lower Jurassic F-II member (Fjerritslev Formation) on the Skagerrak–Kattegat Platform; the muddy sandstones were deposited by coastal progradation and ensuing transgression (sequences Fj 4, Fj 5; Figs 8, 12; Nielsen 2003). The sandstones are only well developed north-east of the Børglum Fault, where they show good porosity.

In the south-eastern part of the study area, a series of Lower Jurassic (Sinemurian–Pliensbachian) shoreface sandstones were encountered in the Lavø-1 and Margretheholm-1 wells, where they interfinger with marine mudstones of the Fjerritslev Formation. The sandstone unit is 30–70 m thick with porosities of 10–25%.

The shoreface sandstones present in the lower and upper parts of the Upper Jurassic Flyvbjerg Formation are also considered potential reservoir rocks; these sandstones show a general thinning from north to south and from east to west (Figs 8, 13).

On the Skagerrak–Kattegat Platform, the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation includes shallow marine and fluvial sandstones that possess reservoir properties, although the shale content increases rapidly towards the basin.

Discussion

The evaluation presented here of potential source rocks in the Danish portion of the Norwegian–Danish Basin, together with a review of potential reservoirs, suggests that a Mesozoic petroleum system may be present. Two primary plays are possible: the Upper Triassic – lowermost Jurassic Gassum play and the Middle Jurassic Haldager Sand play, both relying on charge from Lower Jurassic (Toarcian) or uppermost Jurassic – lowermost Cretaceous source rocks. Both plays have, however, been tested with negative results in a number of wells. It is generally proposed that the main reason for the failure of these plays so far has been the insufficient maturation (burial depth) of the potential source rocks. In the light of this study, then, it is useful to revisit the important elements of the Mesozoic petroleum system.

Source-rock quality and distribution

The regional petroleum generation potential and thermal maturity of the pre-Upper Cretaceous succession in the study area have been assessed by evaluating the stratigraphic units drilled by 33 wells both onshore and offshore in the Skagerrak and Kattegat areas (Fig. 1). It is generally accepted that the Upper Cretaceous – Cenozoic strata have no source-rock potential in the study area. Within the Lower Palaeozoic – Lower Cretaceous succession, only the Lower Jurassic (Toarcian) F-III and F-IV members of the Fjerritslev Formation and the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation contain intervals that qualify as potential oil-prone source rocks in the successions drilled to date (Figs 25–27, 34–38). None of these potential source rocks have a basinwide distribution. It is further emphasised that only parts of the lithostratigraphic units have a good to excellent petroleum generation potential and the potential source-rock units have highly variable generation potentials depending on the interaction of a number of geological processes during their formation. An overall upwards increasing petroleum generation potential is observed from the F-I member to the upper F-III and F-IV members of the Lower Jurassic Fjerritslev Formation (Figs 23, 24, 26, 27). This difference in generation potential is partly attributed to a change in depositional conditions through Early Jurassic times (Thomsen *et al.* 1987; Michelsen 1989b; Nielsen 2003). The F-I and F-II members were deposited in more oxic and shallow marine environments with a higher contribution of Type III kerogen, whereas the F-III and F-IV members were deposited under more reducing bottom conditions with a higher contribution of oil-prone Type II kerogen (Figs 28, 33).

The generation potential of the Toarcian part of the F-III and F-IV members shows significant lateral changes, with the best-developed source-rock units occurring in the basin centre (Fig. 35A; Table 2). The source quality of the F-III member seems to be particularly well developed in the Mors-1, Kvols-1, Hyllebjerg-1 and Farsø-1 wells, where the average HI values indicate a gas/oil generation potential (Fig. 34A). The Mors-1 well is located close to a major salt diapir (Fig. 3), which may suggest that the good source-rock quality is related to deposition in the deeper rim syncline of the diapir. It is likely that development of rim synclines adjacent to salt structures influenced source-rock formation, and it may thus be possible to infer the presence of source-rock intervals based on the analysis of lateral changes in seismic attributes in the rim synclines. Indeed, Thomsen *et al.* (1987) suggested that the increased HI values and TOC contents in Kvols-1 were the result of anoxic depositional conditions in a rim syncline; note, however, that this well was drilled adjacent to a minor salt pillow rather than a diapir. Michelsen (1989b) proposed that the organic-rich section in the Kvols-1 well resulted from reduced siliciclastic influx and constant organic deposition (i.e. a condensed section) as reflected in the relatively thin succession between TS 15 and the base of the F-IV member compared to other wells; this interpretation is compatible with the fact that the highest HI values seem to be related to MFS 15 (Fig. 29A). The Hyllebjerg-1 and Farsø-1 wells were not drilled close to salt structures, but both wells are located in the deepest part of the Himmerland Graben (Figs 2, 3). In Hyllebjerg-1, the highest HI values actually occur in the basal part of the F-IV member immediately above SB 16, which may suggest a relationship to a transgressive surface (Fig. 32A). The Rønde-1 well is located on the eastern flank of the Voldum structure, but the F-III member is not developed as a good source rock in this well. In contrast, the well-developed source rocks occur in the F-IV member and they do not seem to be associated with either maximum flooding or transgressive surfaces (Fig. 29B). It is commonly assumed that the formation of marine black mudstones with high values of HI is associated with initial flooding of lowstand systems creating sediment-starved environments with sufficient nutrients for high organic production (e.g. Wignall & Maynard 1993). During continued transgression, organic-rich black shales may be preserved. The formation of oil-prone shales is also considered to occur at the time of maximum marine flooding, and they are often best developed in the upper part of the transgressive systems tract close below the maximum flooding surface (Bohacs 1993; Robison & Engel 1993; Pasley *et al.* 1993). It is clear, however, from Figs 29–32 that no simple relationship exists in this case between the sequence stratigraphic key surfaces and high HI values.

The data from the wells analysed in this study thus indicate that the potential oil source rocks occur in different intervals within the Toarcian part of the F-III and F-IV members. These intervals may be locally developed, and 2–4 stacked intervals occur in some areas. The combined F-III and F-IV members in the Rønde-1, Kvols-1 and Haldager-1 wells, for example, possess oil-prone net source-rock intervals (i.e. HI >200 mg HC/g TOC) with average HI values ranging from 294–404 mg HC/g TOC, whereas the net source-rock interval in other wells is less oil-prone (Fig. 35A). The large variation in net/gross ratio shows that sedimentation rate was not the sole controlling parameter (Fig. 35A), but rather that optimum conditions required the right combination between sedimentation rate and organic productivity. Local depressions in the basin may further have favoured preservation of the organic matter by promoting stratification of the bottom waters. A detailed analysis of outcrops and cores from the Lower Toarcian Posidonia Shale in south-west Germany has shown that the formation of this rich source rock was governed by a complex interplay of factors, important amongst which was water column stratification controlled by sea-level changes (Röhl *et al.* 2001). Stratigraphic subdivision of the Danish well sections (Michelsen 1989a; Nielsen 2003) indicates that the two lower intervals of organic-rich mudstones in the F-III member are similar in age to the organic-rich shales in the Falciferum and Bifrons Zones of the Posidonia Shale. This suggests that, in addition to local factors, external factors such as regional/global anoxic events and sea-level changes may have played an important role in the formation of organic-rich shales at this time in the Norwegian–Danish Basin and the Fennoscandian Border Zone. The regional or global anoxia in the Early Toarcian that seems to have favoured the formation of organic-rich mudstones at some stratigraphic levels in parts of the basin, was apparently not a significant factor in other areas, possibly owing to high clastic input or shallow water depth that prevented the development of oxygen-deficient conditions and thus masked the event. It is intriguing, however, that the anoxic event appears to have influenced deposition along the basin margin in shallow marine/lagoonal areas on Bornholm (Koppelhus & Nielsen 1994; Hesselbo *et al.* 2000). The implication is, therefore, that the deposition and preservation of marine organic matter in the basin was a complex interplay between a number of factors probably including bottom topography and depth, variation in primary organic productivity, sedimentation rate, bottom-water oxygenation and distance to fluvial sources and coastlines; the relative importance of these different factors in influencing source-rock formation in the area is poorly understood in detail.

In contrast to the uncertainty related to regional prediction of source-rock quality, the present-day geographical occurrence of the stratigraphic interval spanning the F-III and F-IV members is well understood (Fig. 15). Their occurrence is primarily dependent on the regional early Middle Jurassic uplift event that caused deep widespread erosion, with truncation of the source-rock interval over large parts of the study area. Indeed, even within the central area where the F-III and F-IV members are typically preserved (Figs 15, 25B), this interval may be absent over local structural highs such as salt structures. To assess the distribution of this interval, it is necessary to map seismically both the base Middle Jurassic unconformity (base Haldager Sand Formation or Bryne Formation) and the seismic reflector corresponding to top F-II member. The latter coincides with a significant Upper Pliensbachian flooding surface typically situated 100–200 m below the best source-rock intervals. If possible, reflectors between these two horizons should also be mapped out in order to further constrain the position of the potential source rocks.

Parts of the uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation, which is dominated by siltstones and sandstones in most wells, possess a petroleum generation potential in the Hyllebjerg-1, Skagen-2, Terne-1 and Voldum-1 wells, with the Terne-1 well having a particularly rich *c.* 160 m thick oil-prone interval with an average HI of 478 mg HC/g TOC (Fig. 38A; Table 3). The Type I kerogen composition of this Terne-1 interval (Fig. 39) indicates, however, freshwater to slightly brackish lacustrine depositional conditions in contrast to the marine and paralic conditions that characterised the regional depositional environment of the formation; the unit may thus be only a local development in the Terne-1 area in the Kattegat.

Source-rock maturity

Regional maturation profiles constructed from VR measurements corrected for post-Early Cretaceous exhumation yield a likely depth to the top of the oil window (VR of 0.6%R_o) of *c.* 3050–3100 m, based on the regional coalification curves principally derived from onshore wells (Figs 20A, 22A). Accepting this depth, the potential source rocks

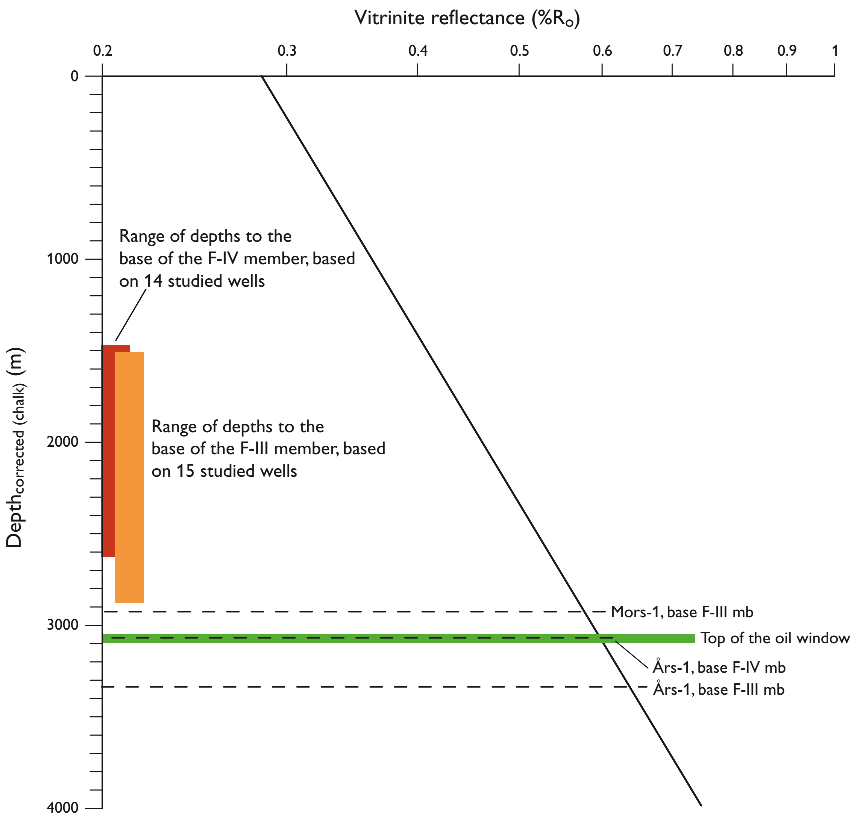
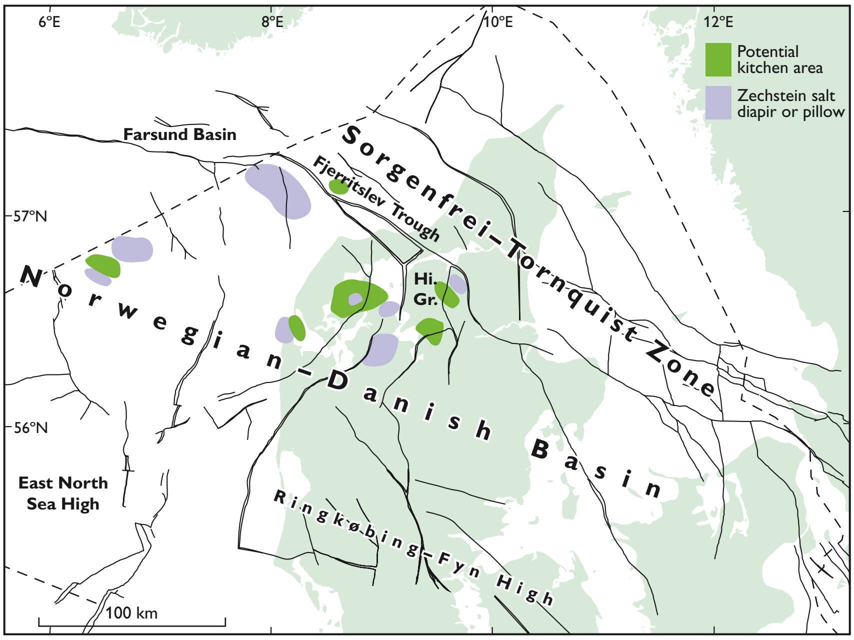


Fig. 40. The regional VR curve based on chalk velocity corrected depth (see Fig. 22A). The depth to the top of the oil window at 0.6%R_o is indicated together with the range of depths to the base of the F-III and F-IV members before post-Early Cretaceous exhumation in the studied wells. In the Mors-1 well, the base of the F-III member has been buried slightly deeper, but still above the top of the oil window. Only in the Års-1 well has the F-III member been within the top part of the oil window before exhumation. The thickness of the F-III member ranges from 30–279 m in the 15 studied wells, whereas the F-IV member ranges from 9–127 m in 13 of the 14 studied wells. In Gassum-1, the F-IV member is considerably thicker, namely 320 m.

need a burial depth of *c.* 1.75–2 sec. TWT to reach the oil window if velocity data from the Års-1 well, placed centrally in the basin, are used as guidelines (Nielsen & Japsen 1991). The shales of the Frederikshavn Formation are thus regionally thermally immature in the study area. The Toarcian shales of the F-III and F-IV members of the Fjerritslev Formation constitute the most obvious potential source rocks, but over most of the study area they have not been buried sufficiently to have entered the oil window (Fig. 40). Of the investigated wells, only in the Års-1 well, on the flank of the Himmerland Graben immediately west of a major salt structure, has the F-III member been within the uppermost part of the oil window prior to post-Early Cretaceous exhumation. The source-rock quality of the F-III member in this well, however, is poor with a maximum HI value of 186 mg HC/g TOC and an average HI of only 113 mg HC/g TOC. Hence, occurrence of mature source rocks in the study area requires local burial anomalies, such as local grabens or rim synclines adjacent to salt diapirs, to reach thermal maturity for oil generation.

A map showing the depth to the base of the Middle Jurassic (i.e. the base Middle Jurassic unconformity) in the Danish part of the Norwegian–Danish Basin was constructed by Bidstrup *et al.* (2002). This surface corresponds to the top of the F-IV member, i.e. the top of the stratigraphic unit with the most promising source rocks (F-III and F-IV members) in the Fjerritslev Formation. If the present-day depths are corrected for post-Early Cretaceous uplift (Table 1; Japsen 1998) and information of the combined thickness of the F-III and F-IV members (Fig. 25) is included, it is possible to locate potential areas with mature source rocks (Fig. 41). These potential, locally developed petroleum kitchens are mainly located in the central part of the study area (central–northern Jylland), where they are associated with rim synclines of salt structures. Offshore, in the Skagerrak, a minor kitchen may be present in the Fjerritslev Trough close to the Fjerritslev Fault. Farther to the west, a kitchen may occur between two salt structures (Fig. 41) although in this area the F-III member is probably very thin and the F-IV member is absent (Fig. 25). The onshore petroleum kitchens indicated on Fig. 41 correspond to the possible kitchens in the Harboør–Uglev, Mors and Tostrup rim synclines mapped by Thomsen *et al.* (1987); apart from the kitchen area in the Mors rim syncline, however, the kitchens identified in the present study are areally smaller. The potential kitchen in the Vejrum rim syncline suggested by Thomsen *et al.* (1987) cannot be confirmed in the present study, principally due to very thin source-rock units (e.g. Mejrup-1 well; Fig. 25A) or the absence of the F-III and F-IV members (Fig. 15).

Fig. 41. Map showing the location of potential petroleum kitchen areas with mature source rocks of the F-III and F-IV members of the Lower Jurassic Fjerritslev Formation. The kitchens are locally developed and are principally associated with salt structures. The most westerly kitchen in the Skagerrak is highly uncertain due to the absence of the F-IV member and possibly only a very thin (or absent?) F-III member. Note that only salt structures associated with potential kitchen areas are shown (cf. Fig. 3). **Hi. Gr.**, Himmerland Graben.



The Mors-1 well is located adjacent to the northern flank of the largest potential kitchen area. The main targets of this well were the Zechstein and Rotliegend, but the well reached TD in Lower Triassic sandstones at a depth of 5303 m. The well intersected 123 m of net source rock with gas and oil generation potential (average HI = 221 mg HC/g TOC) and the source rocks are close to being early mature (Fig. 35). The well encountered only small traces of asphalt in the Haldager Sand Formation, and the poor hydrocarbon indications may be explained by the lack of structural closure (Thomsen *et al.* 1987; GEUS, unpublished data).

Reservoirs and migration

Both reservoirs, the Gassum and Haldager Sand Formations, are proved to be present regionally and sealed by Lower Jurassic and Upper Jurassic mudstones, respectively. The Haldager Sand reservoir conformably overlies the Lower Jurassic potential source rocks in the relatively deep Fjerritslev Trough and presumably also in the Farsund Basin (Fig. 2). In contrast, in the remaining parts of the study area, where the F-III and F-IV members and the Haldager Sand Formation are present, the Haldager Sand reservoir unconformably overlies the succession with the potential source rocks. Migration of hydrocarbons to the Haldager Sand reservoir is thus simple. Migration to the Gassum reservoir requires stratigraphic downward migration of the hydrocarbons and may thus require structural components, i.e. faulting or salt domes.

Thin fine-grained shoreface sandstones formed during short-lived regressive events occur within the Lower Jurassic marine mudstones in the Fjerritslev Trough and Skagerrak–Kattegat Platform. These sandstones can be traced relatively far into the basin as thin silty sandstone intercalations in the mudstones and may function as conduits for hydrocarbon migration.

The Gassum Formation reservoir is overlain by the laterally consistent, thick marine mudstone succession of the Fjerritslev Formation. Sandstone or siltstone units up to 5–10 m thick are present in the basal Fjerritslev Formation in places, but their influence on seal integrity over the Gassum Formation reservoir is generally expected to be limited. Close to the basin margin, however, for example on the Skagerrak–Kattegat Platform in the eastern part of Kattegat and Sjælland, Hettangian–Pliensbachian sandstones are common and constitute an additional potential reservoir, overlain by marine mudstones of the upper Fjerritslev Formation. The Haldager Sand reservoir is overlain by marine mudstones of the Flyvbjerg and Børglum Formations. Sandstones are present in the lower and upper part of the Flyvbjerg Formation in places, and their thickness and grain size are expected to increase towards the northern and eastern basin margin, where they may form an additional reservoir section. The middle part of the Flyvbjerg Formation is dominated by marine mudstones with some seal capacity, and the Flyvbjerg Formation itself is overlain by the thick, regionally continuous, marine mudstone succession of the Børglum Formation.

Active Mesozoic petroleum system?

In agreement with the general immaturity of the potential source rocks in the study area, very few oil shows have been reported. One exception is the K-1 well (Fig. 1), in which weak shows in sandstone and sandstone stringers were noted at several depths. The well was, however, drilled with diesel that was added several times during drilling operations; geochemical data of cuttings samples from the K-1 well show the presence of a low-boiling distillation cut such as diesel, with a minor contribution representing indigenous immature organic matter (GEUS, unpublished data). Thus, reports of thermally generated petroleum in this well cannot be confirmed. The well was also drilled in an area in which the presence of mature source rocks is deemed unlikely (Fig. 41). The presence of generated petroleum in the Danish part of the Norwegian–Danish Basin thus still has to be documented, although it cannot be excluded that petroleum has been generated in localised potential kitchen areas (Fig. 41).

Conclusions

Two primary plays are possible in the study area: the Upper Triassic – lowermost Jurassic Gassum play and the Middle Jurassic Haldager Sand play, both relying on charge from Lower Jurassic (Toarcian) or uppermost Jurassic – lowermost Cretaceous source rocks. Both plays have, however, been tested with negative results. This study shows that two main uncertainties are present in the Danish part of the Norwegian–Danish Basin and the Fennoscandian Border Zone: (1) the patchy distribution of well-developed, oil-prone, potential source rocks, and (2) the thermal maturity of the potential source rocks. The latter factor is considered here to be the most significant uncertainty in proving the integrity of this Mesozoic petroleum system.

The evaluation of source-rock quality, thermal maturity and distribution allows the following principal conclusions to be drawn:

1. Lower Palaeozoic rocks are overmature in the study area and Upper Cretaceous – Cenozoic strata possess no petroleum generation potential.

2. Toarcian marine shales of the Lower Jurassic F-III and F-IV members of the Fjerritslev Formation and the uppermost Jurassic – lowermost Cretaceous shales of the Frederikshavn Formation constitute oil-prone potential source rocks in parts of the basin. The generation potential of these potential source rocks is highly variable geographically, and the F-III and F-IV members in the centre of the basin possess the best-developed source potential. The highly oil-prone lacustrine mudstone interval of the Frederikshavn Formation in the Terne-1 well is probably only a local development.

3. Based on interpretation of regional coalification curves, the top of the oil window (vitrinite reflectance = 0.6%R_o) is located at *c.* 3050–3100 m depth. The uppermost Jurassic – lowermost Cretaceous Frederikshavn Formation had not been buried to this depth prior to post-Early Cretaceous exhumation, and the potential source rocks of the formation are thermally immature in terms of hydrocarbon generation. Similarly, the potential source rocks of the Lower Jurassic F-III and F-IV members of the Fjerritslev Formation are generally immature to very early mature. However, potential kitchen areas with mature source rocks of the F-III and F-IV members may occur in the central part of the study area (central–northern Jylland) and a few places offshore. These potential petroleum kitchens are considered to be of local development, mainly associated with salt structures and grabens (Fjerritslev Trough and Himmerland Graben).

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