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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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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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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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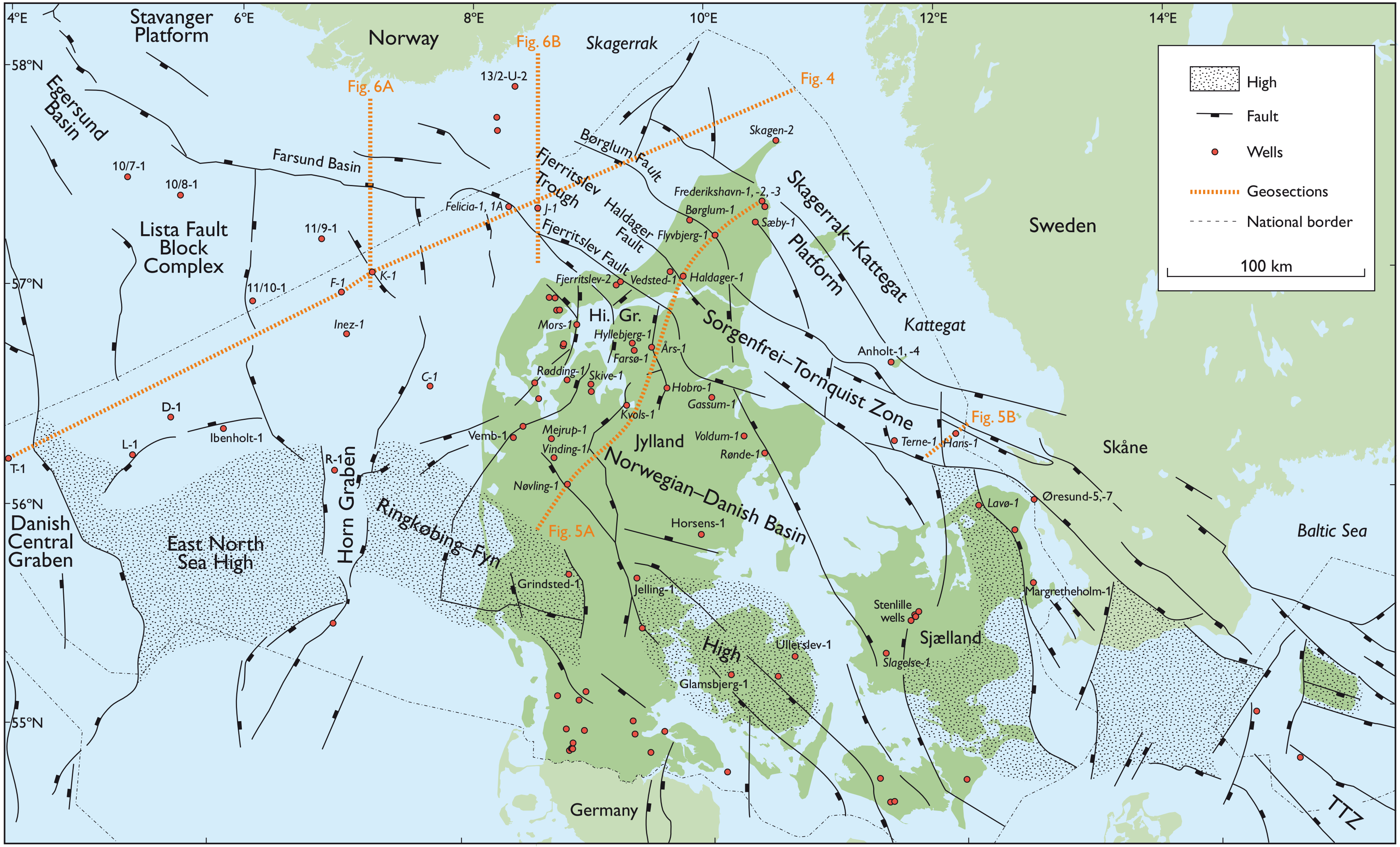


Fig. 1. Map showing well positions and the structural outline of the Norwegian–Danish Basin, the Sorgenfrei–Tornquist Zone, including the Fjerritslev Trough and the Himmerland Graben (**Hi. Gr.**), and the Skagerrak–Kattegat Platform. The major fault systems indicated are those active in the Mesozoic (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.

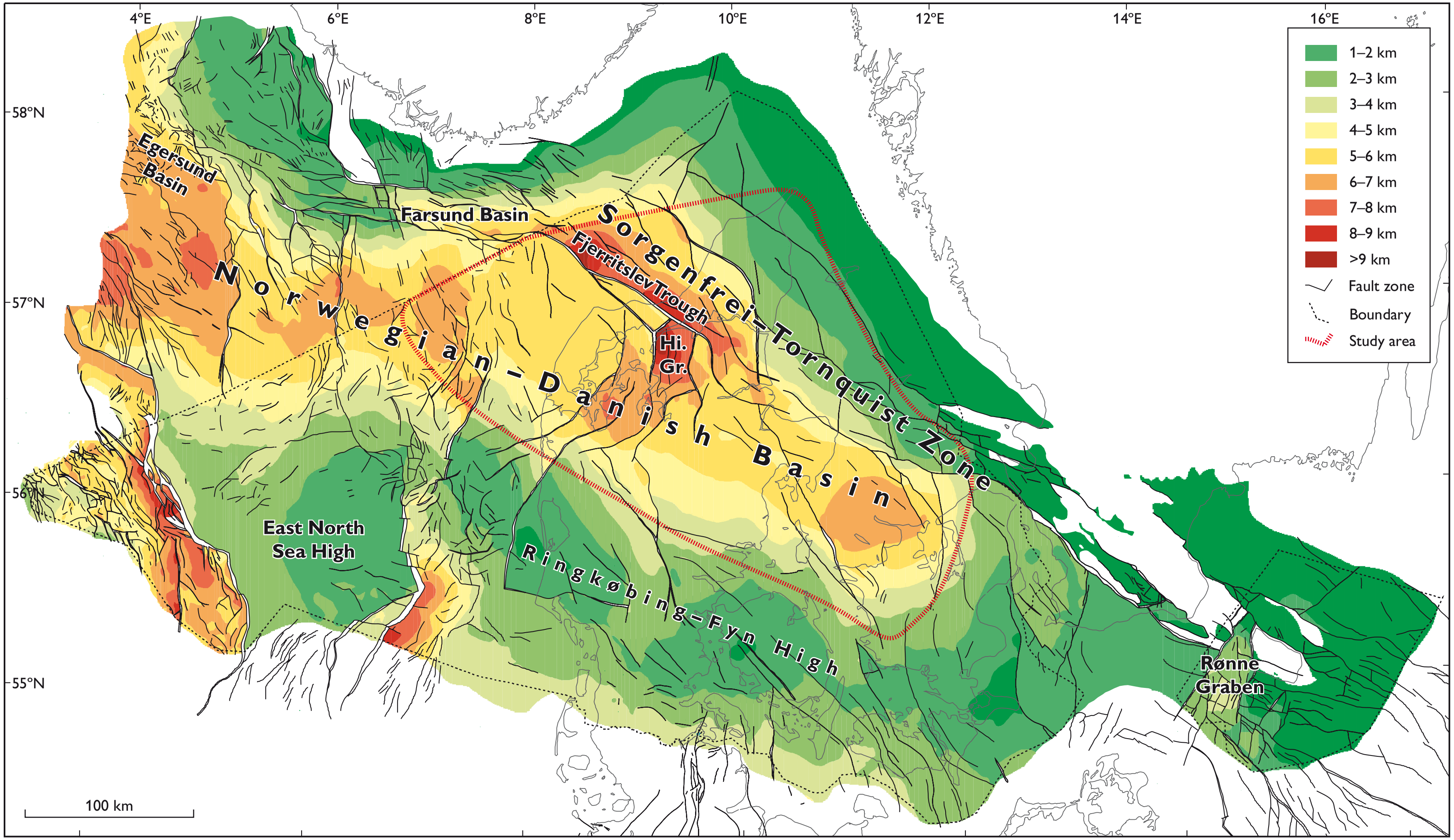


Fig. 2. Depth structure map of the top pre-Zechstein surface, the deepest surface that can be mapped by conventional seismic data in the Norwegian–Danish Basin; the extent of the study area covered by this bulletin is also shown. Note the large thicknesses in the Fjerritslev Trough and the Himmerland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

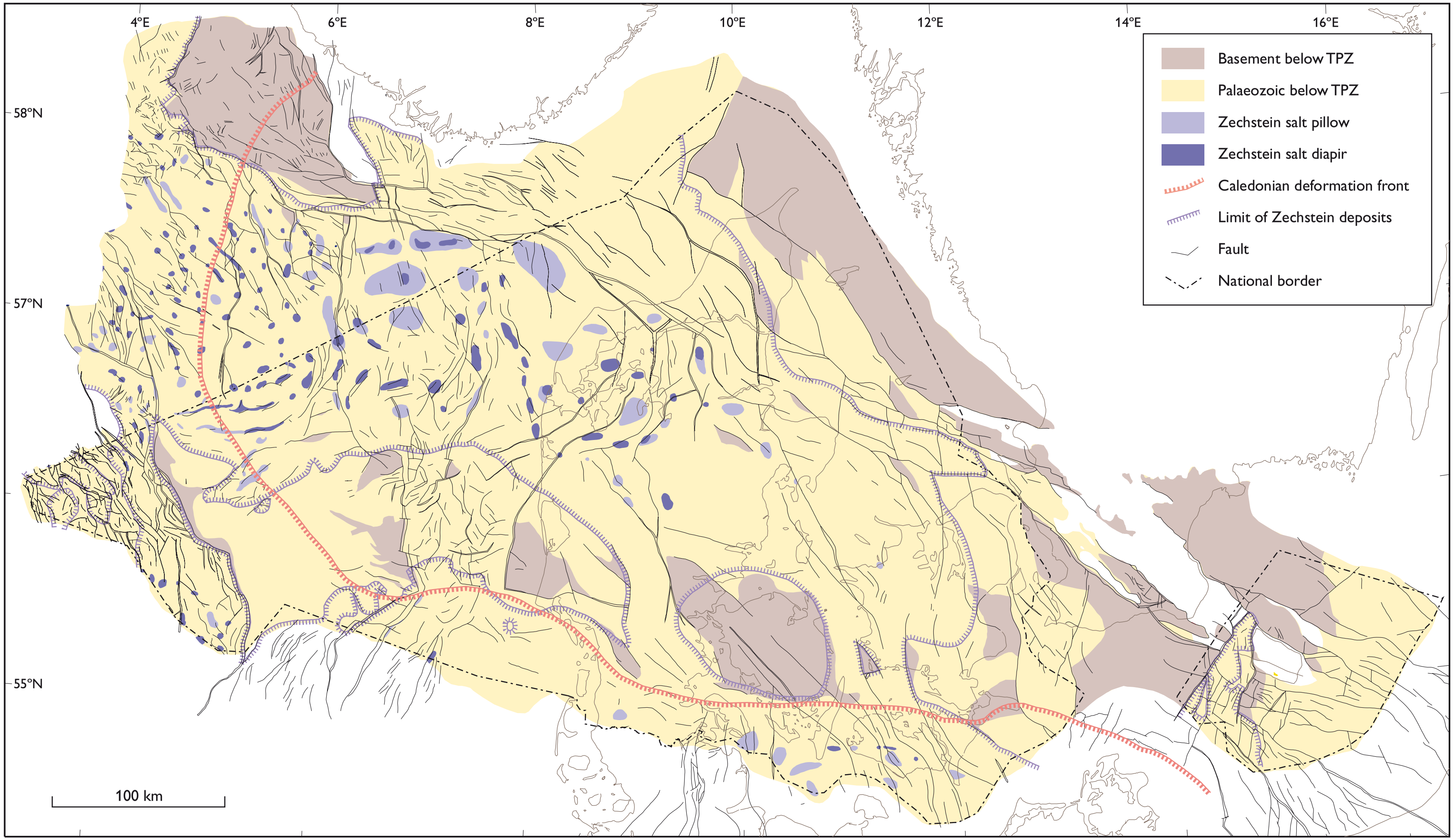
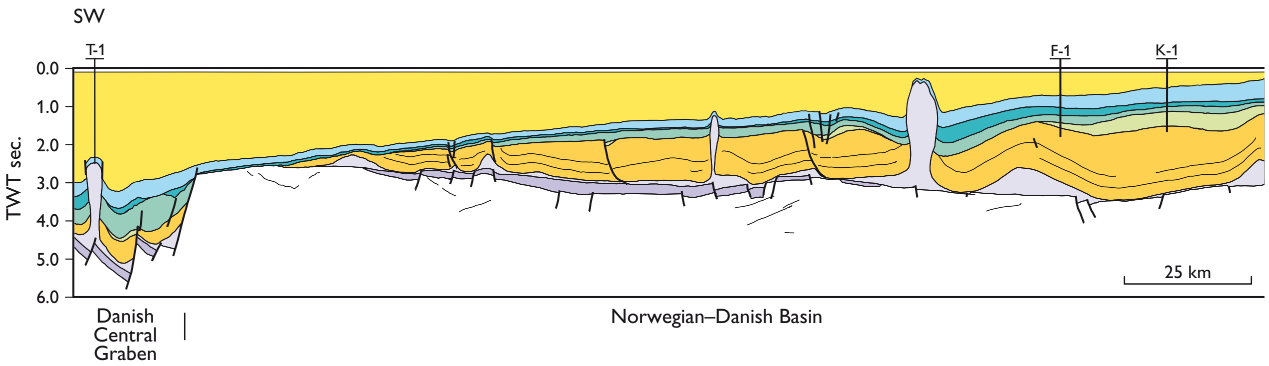


Fig. 3. Map showing the strata subcropping the top pre-Zechstein surface (and lateral correlative surface) and the distribution of known salt structures. The blue line indicates the limit of the Zechstein deposits (Vejbæk 1997). **TPZ**, Top pre-Zechstein.



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

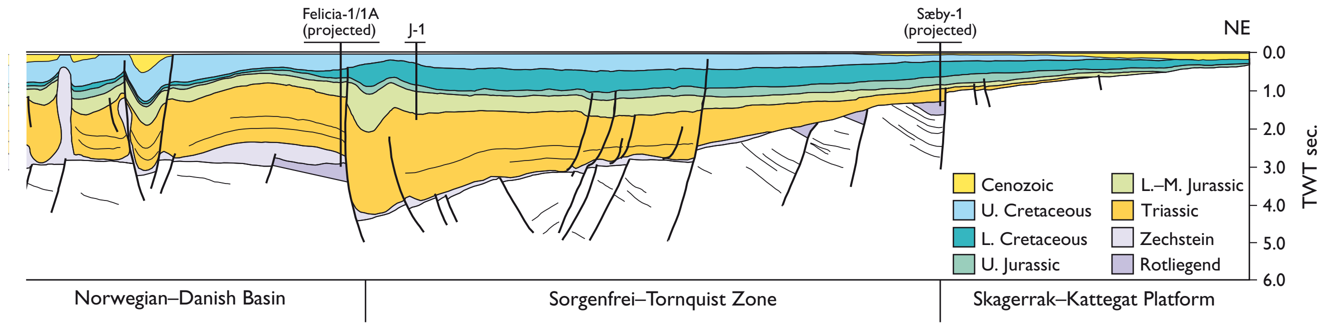


Fig. 4. Regional geosection from the Central Graben in the south-west to the Skagerrak–Kattegat Platform in the north-east showing pinch-out of the Mesozoic strata on the Skagerrak–Kattegat Platform. For location of section, see Fig. 1. **TWT**, Two-Way Travel Time.

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).

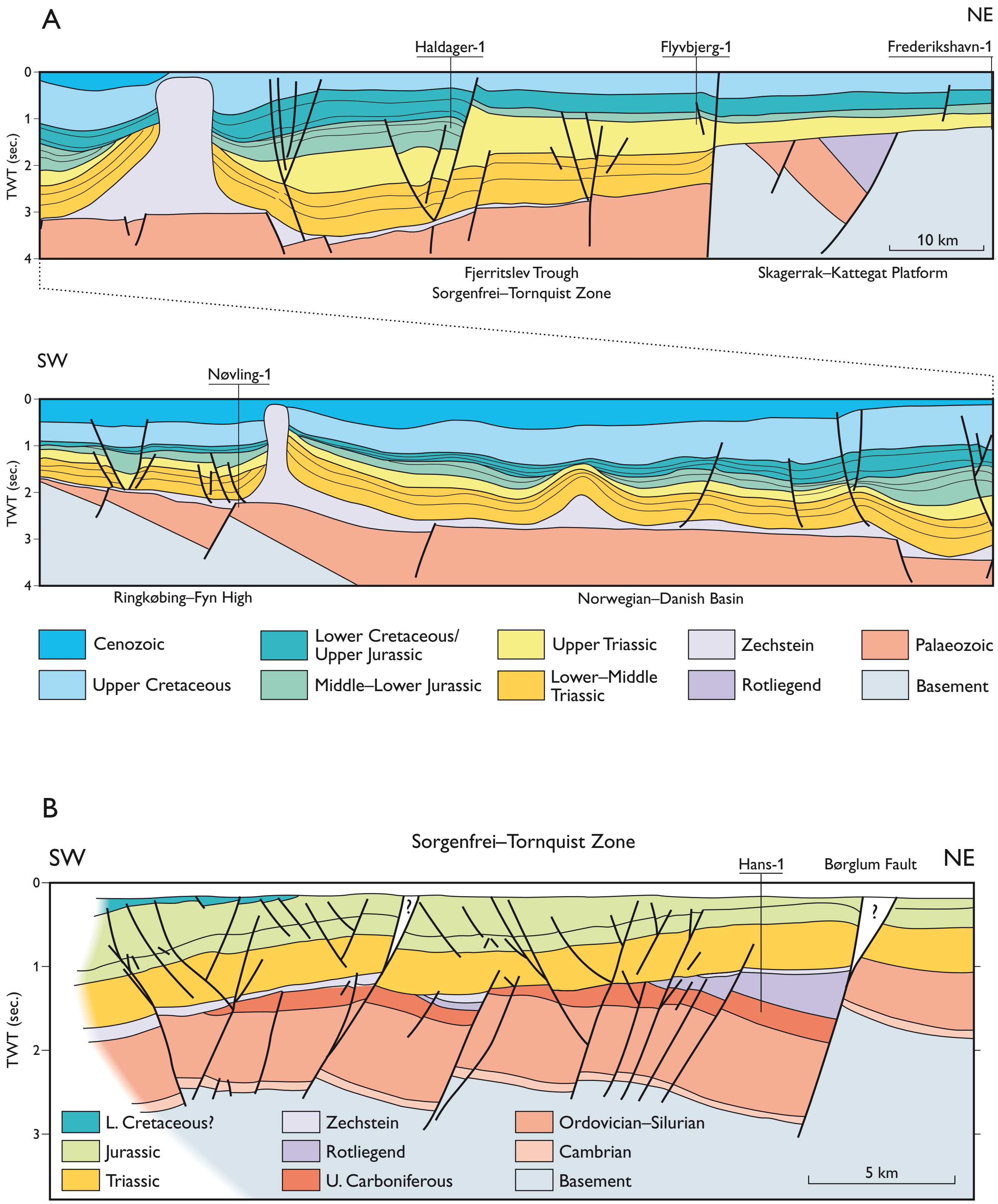


Fig. 5. Geosections modified from Michelsen & Nielsen (1991); for locations, see Fig. 1. **A**: Regional geosection across the Danish part of the Norwegian–Danish Basin showing thickening of the Mesozoic section in the Fjerritslev Trough / Sorgenfrei–Tornquist Zone. **B**: Geosection from the Kattegat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

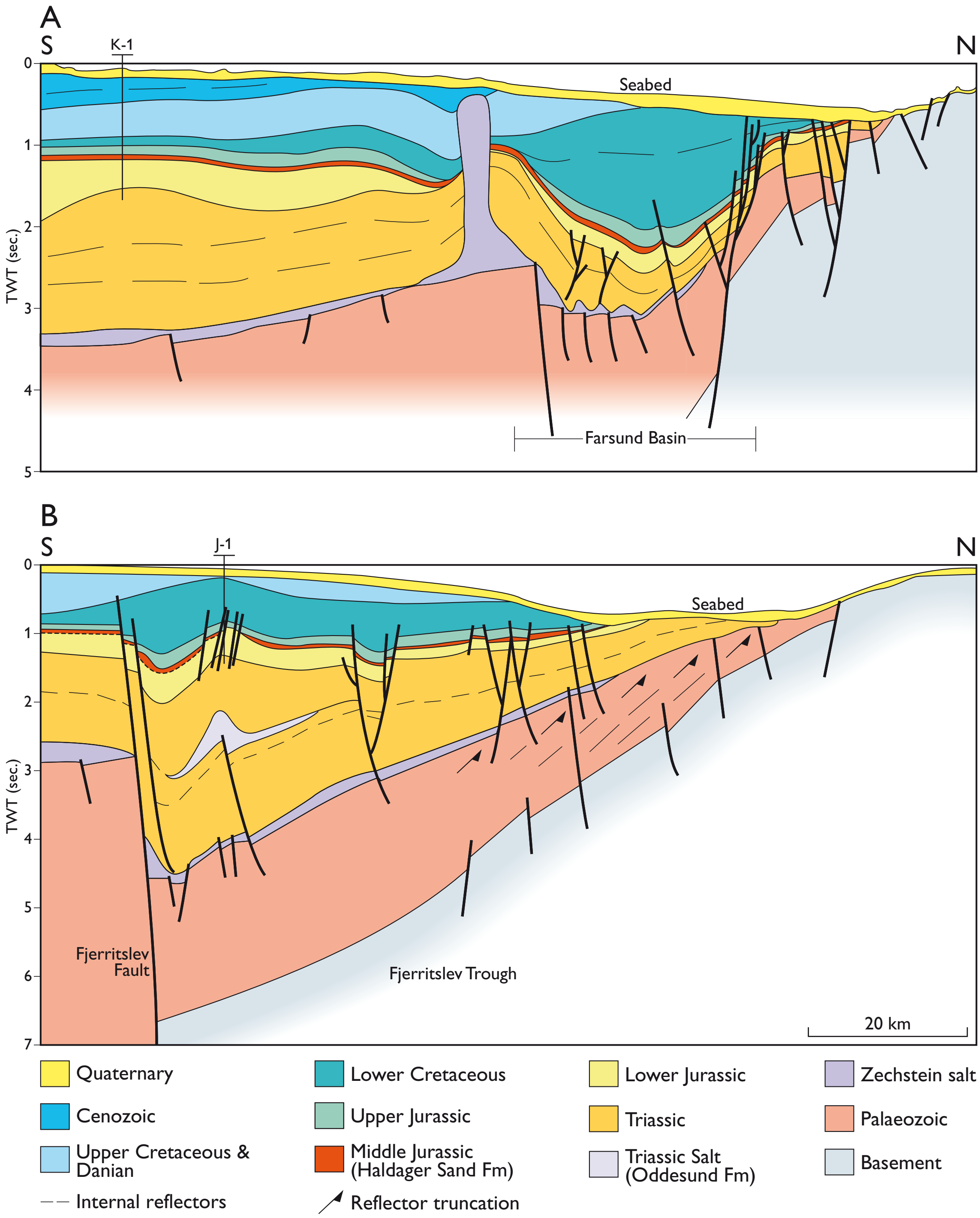


Fig. 6. Geosections modified from Jensen & Schmidt (1993); for locations, see Fig 1. **A**: Geosection from the Norwegian–Danish Basin across the Fjerritslev Fault and the Farsund Basin. The Middle Jurassic Haldager Sand reservoir overlying the Lower Jurassic potential source rocks is marked in red.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

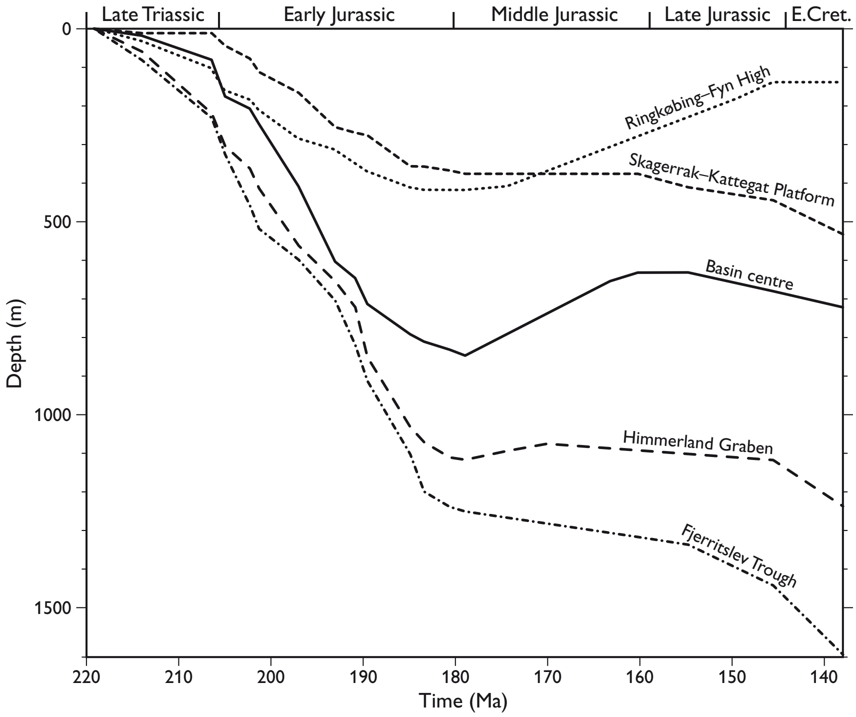


Fig. 7. Subsidence curves for the Late Triassic – Early Cretaceous constructed for different structural elements/sub-basins within the Norwegian–Danish Basin, Skagerrak – Kattegat Platform and Ringkøbing–Fyn High based on a sequence stratigraphic break-down (Nielsen 2003).

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

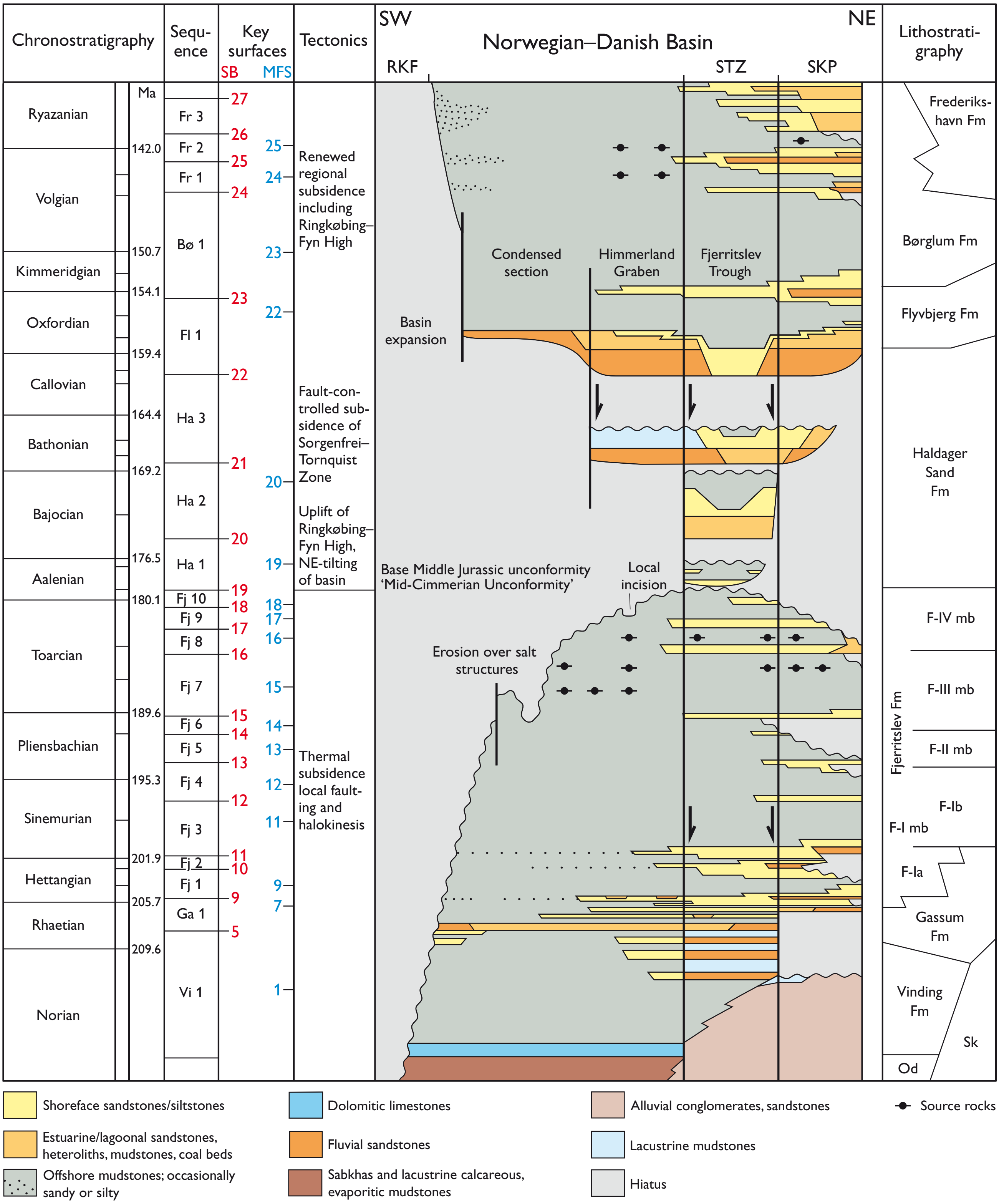


Fig. 8. Time-stratigraphic scheme of the Upper Triassic – Lower Cretaceous trending SW–NE across the Norwegian–Danish Basin. Sequence stratigraphic key surfaces are included, numbered sequence boundaries are shown in red (**SB**) and maximum flooding surfaces shown in blue (**MFS**). The SBs bound the 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.

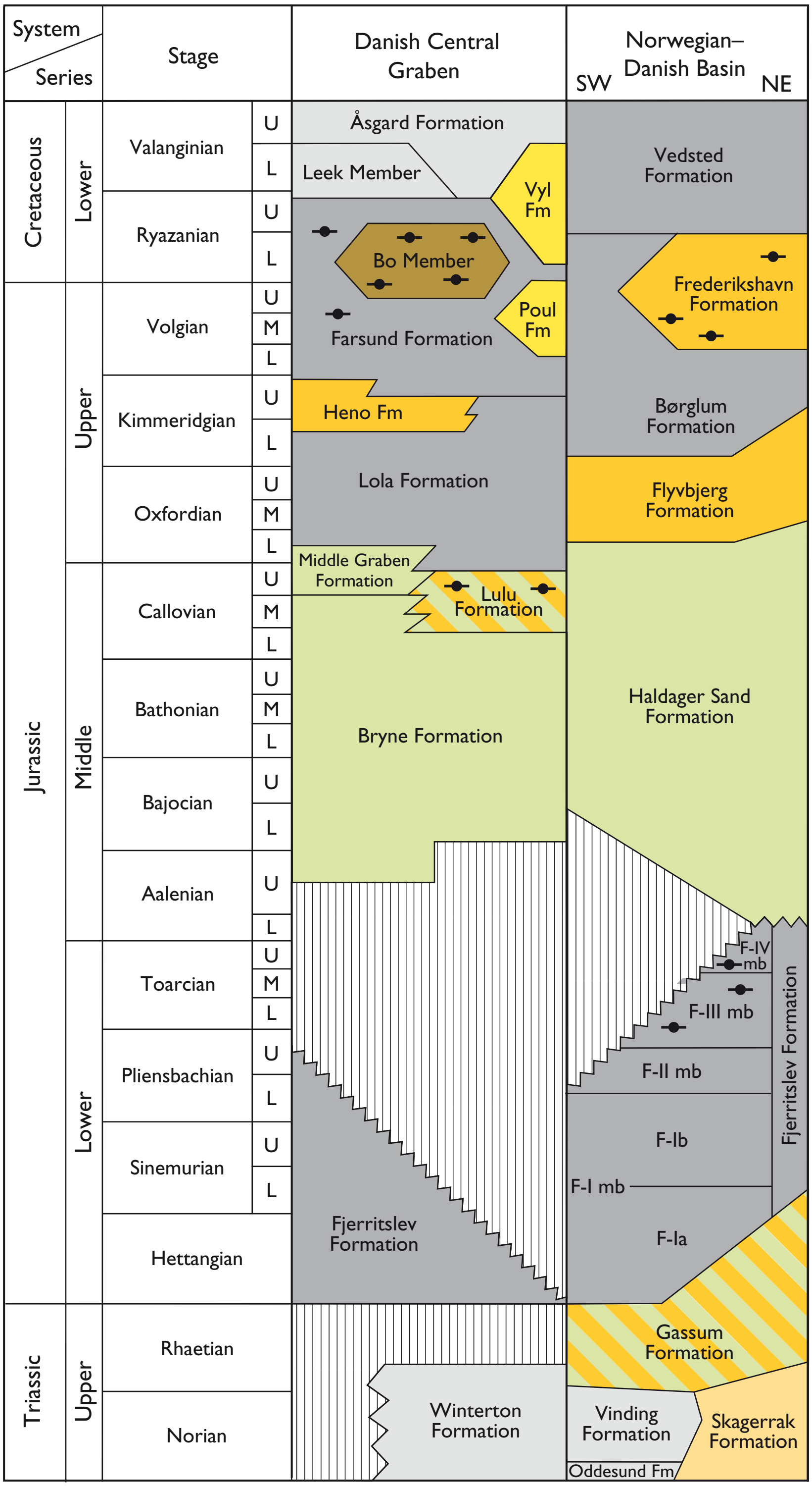
Late Triassic clastic and evaporitic deposition and marine flooding

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-



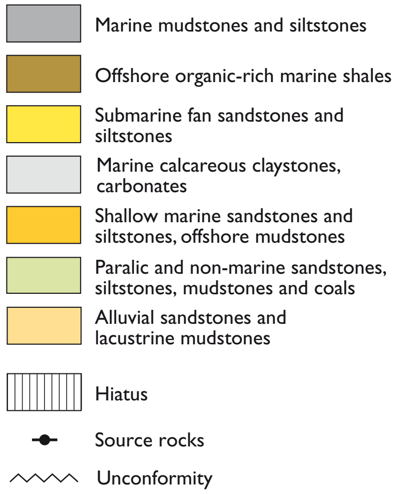


Fig. 9. Lithostratigraphy of the Upper Triassic – Lower Cretaceous in the Norwegian–Danish Basin. The stratigraphy of the Danish Central Graben is included for reference. Modified from Michelsen *et al.* (2003).

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

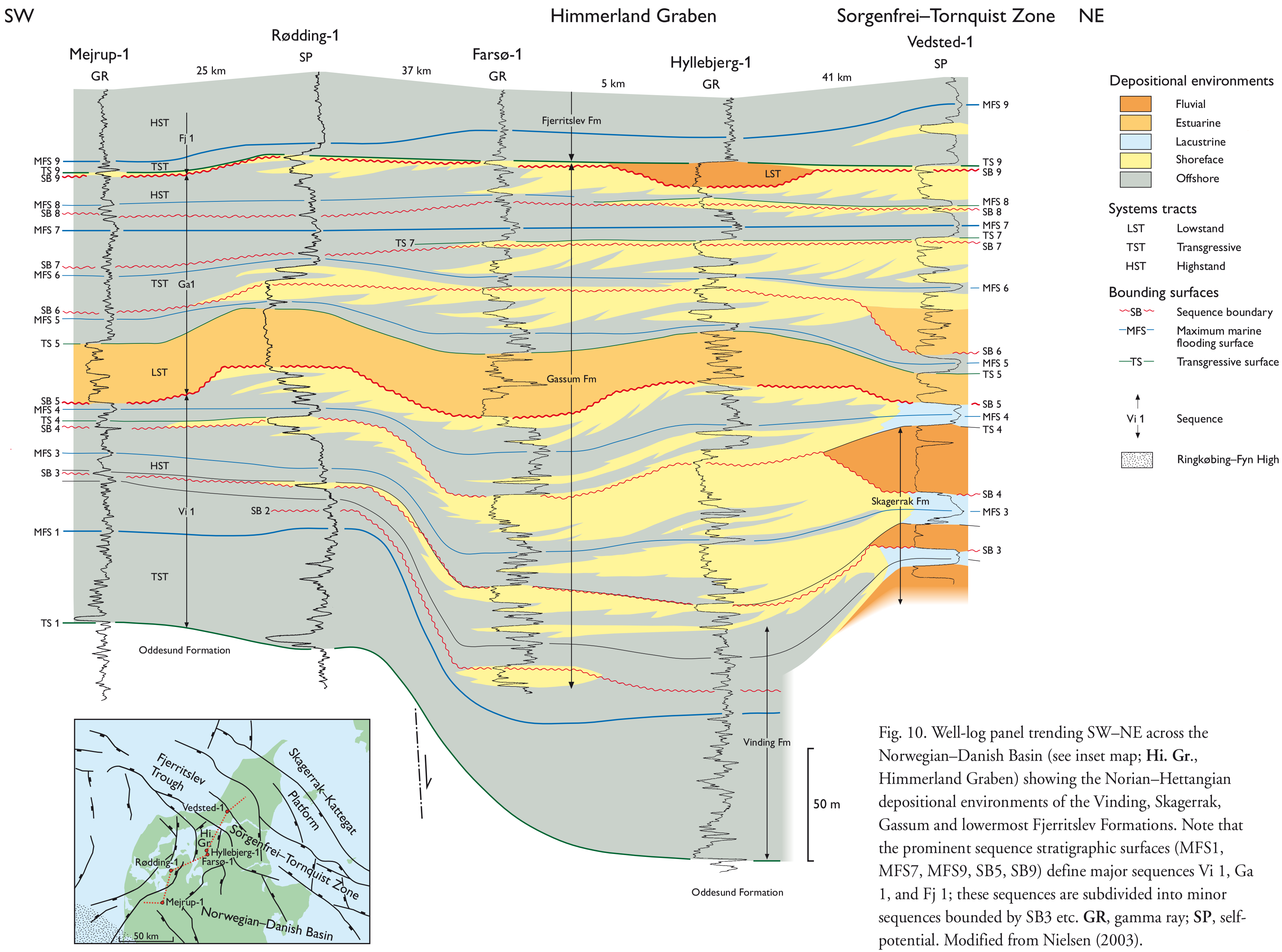


Fig. 10. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Norian–Hettangian depositional environments of the Vinding, Skagerrak, Gassum and lowermost Fjerritslev Formations. Note that the prominent sequence stratigraphic surfaces (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).

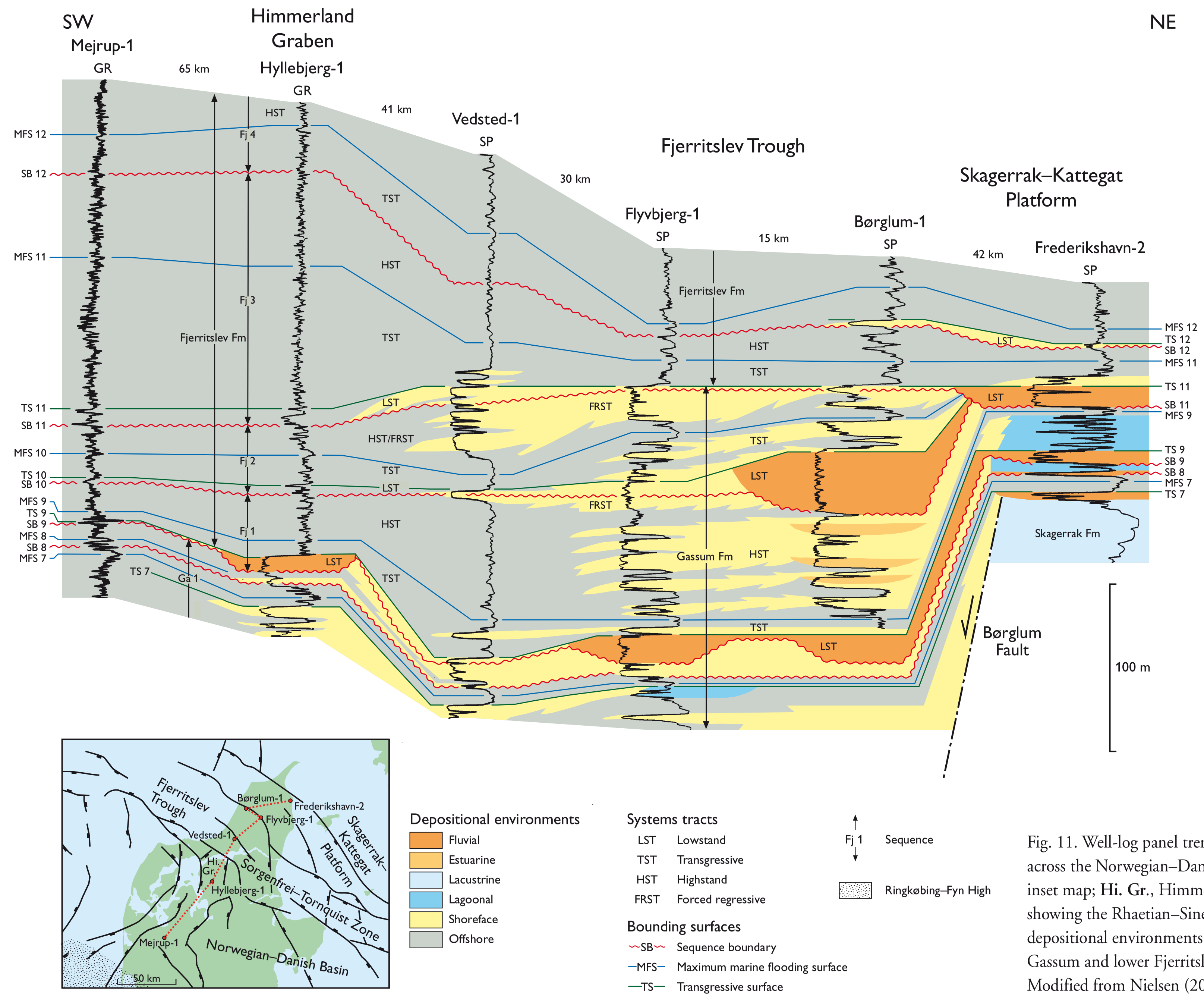


Fig. 11. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Rhaetian–Sinemurian depositional environments of the upper Gassum and lower Fjerritslev Formations. Modified from Nielsen (2003).

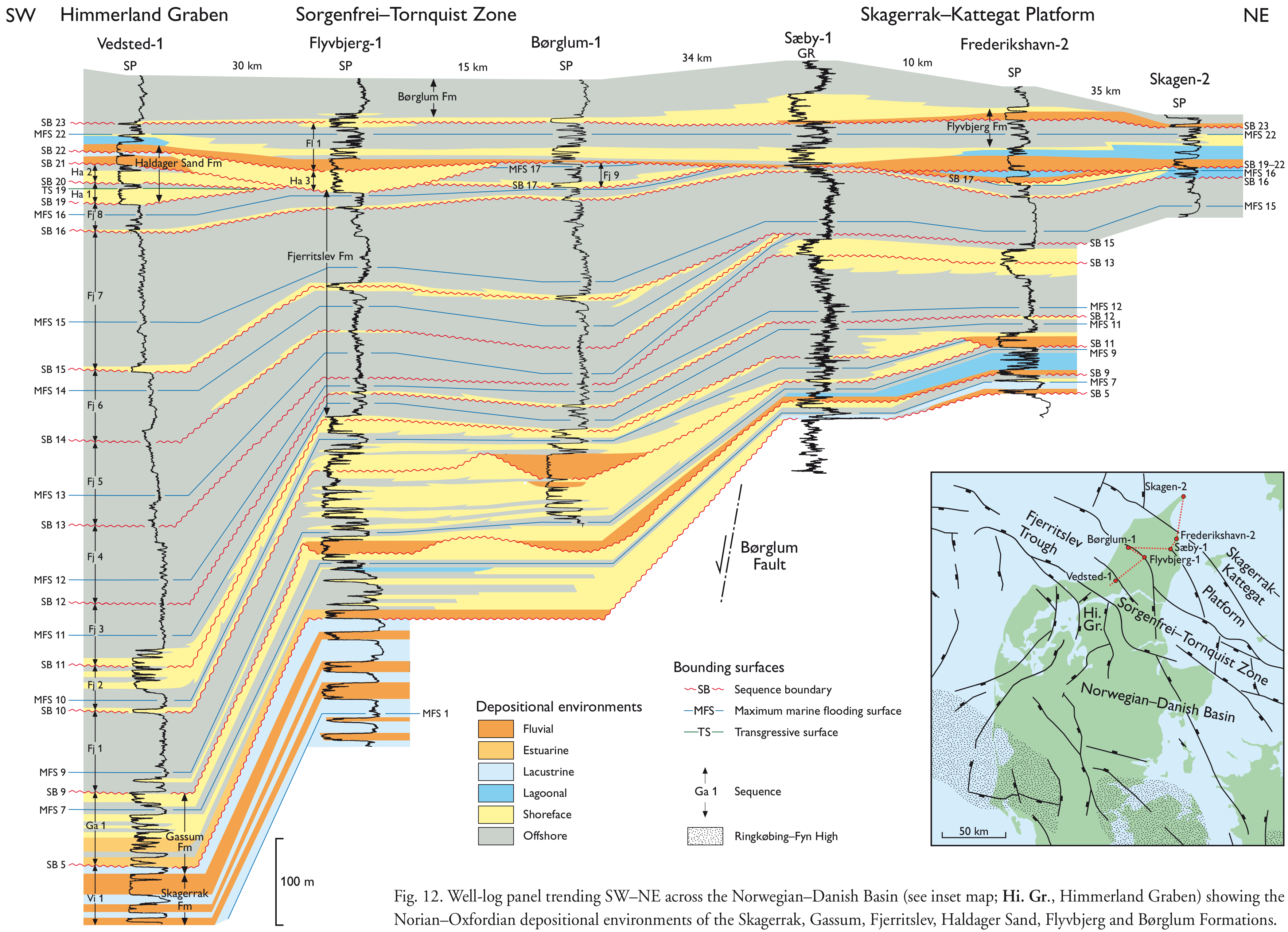


Fig. 12. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Norian–Oxfordian depositional environments of the Skagerrak, Gassum, Fjerritslev, Haldager Sand, Flyvbjerg and Børglum Formations. Note the pronounced erosional truncation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

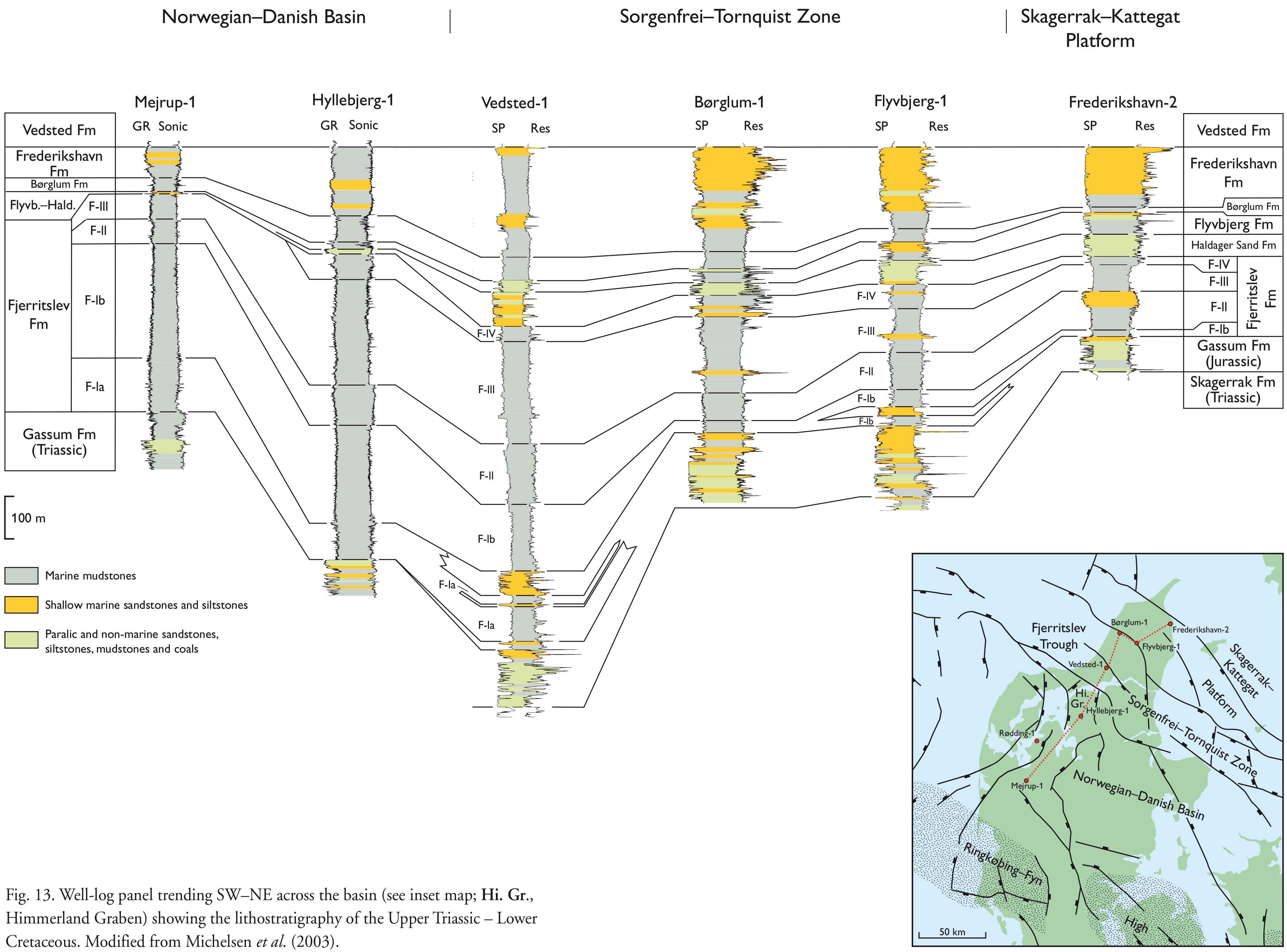


Fig. 13. Well-log panel trending SW–NE across the basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the lithostratigraphy of the Upper Triassic – Lower Cretaceous. Modified from Michelsen *et al.* (2003).

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

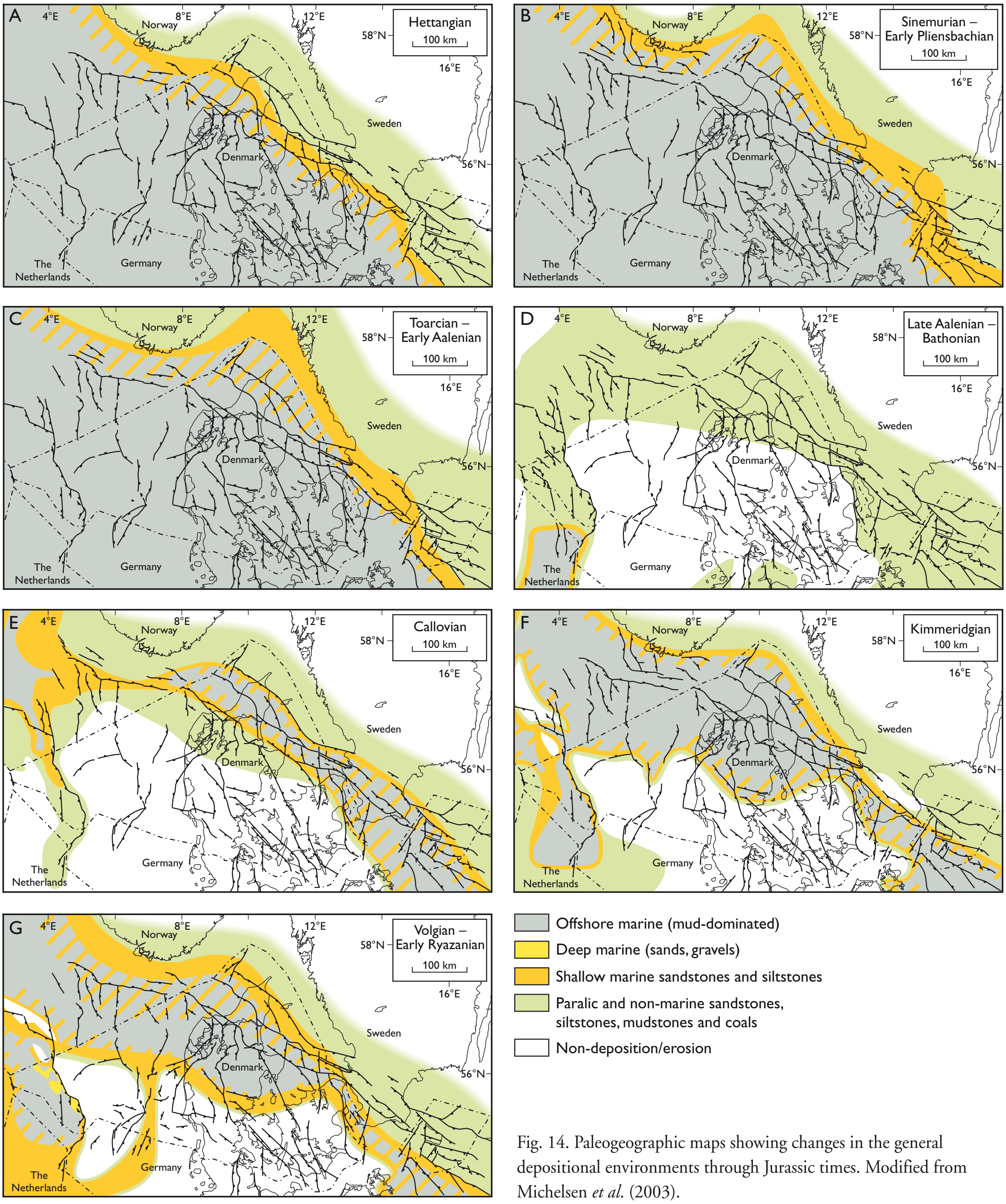


Fig. 14. Paleogeographic maps showing changes in the general depositional environments through Jurassic times. Modified from Michelsen *et al.* (2003).

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

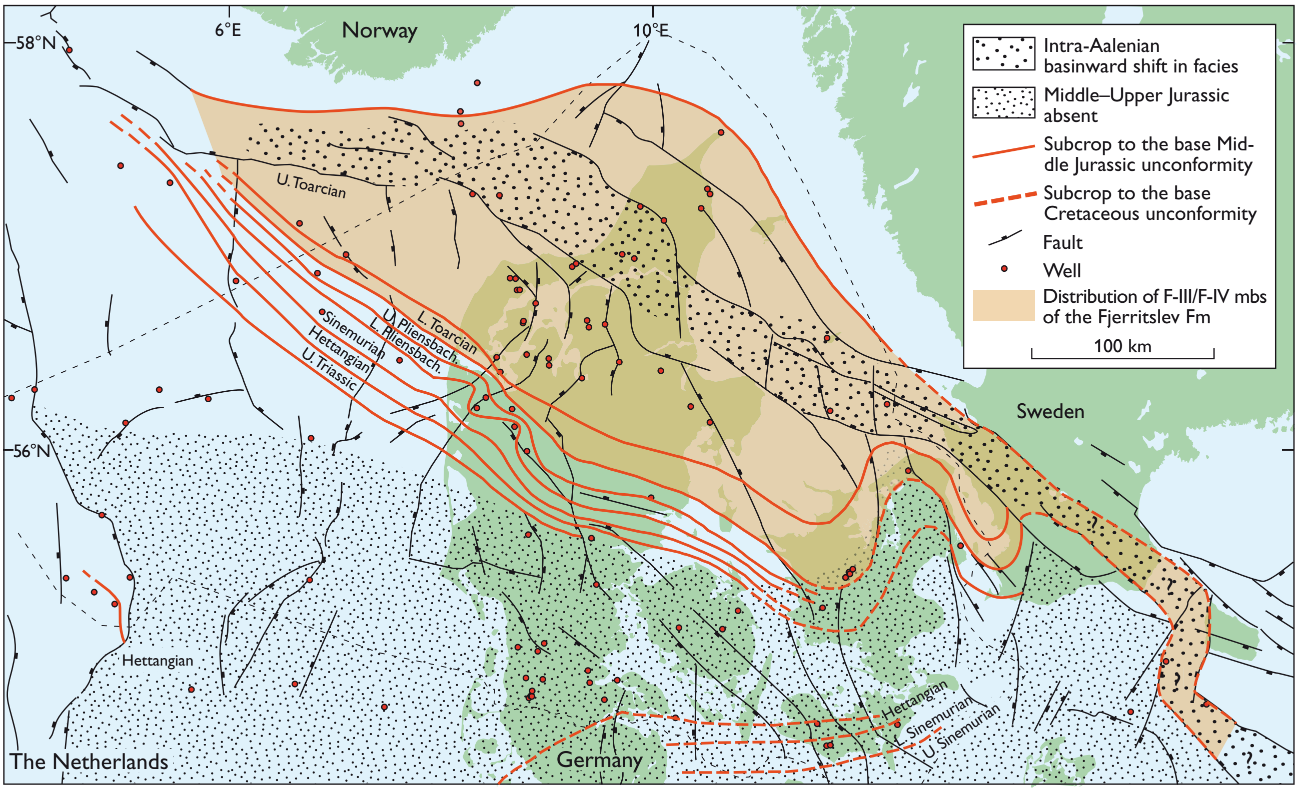


Fig. 15. The subcrop below the base Middle Jurassic unconformity and the distribution of the stratigraphic interval with the Lower Jurassic potential source rocks (F-III and F-IV members). The coarse-dotted area indicates the area within which the shift from marine mudstones to shallow marine or fluvial 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

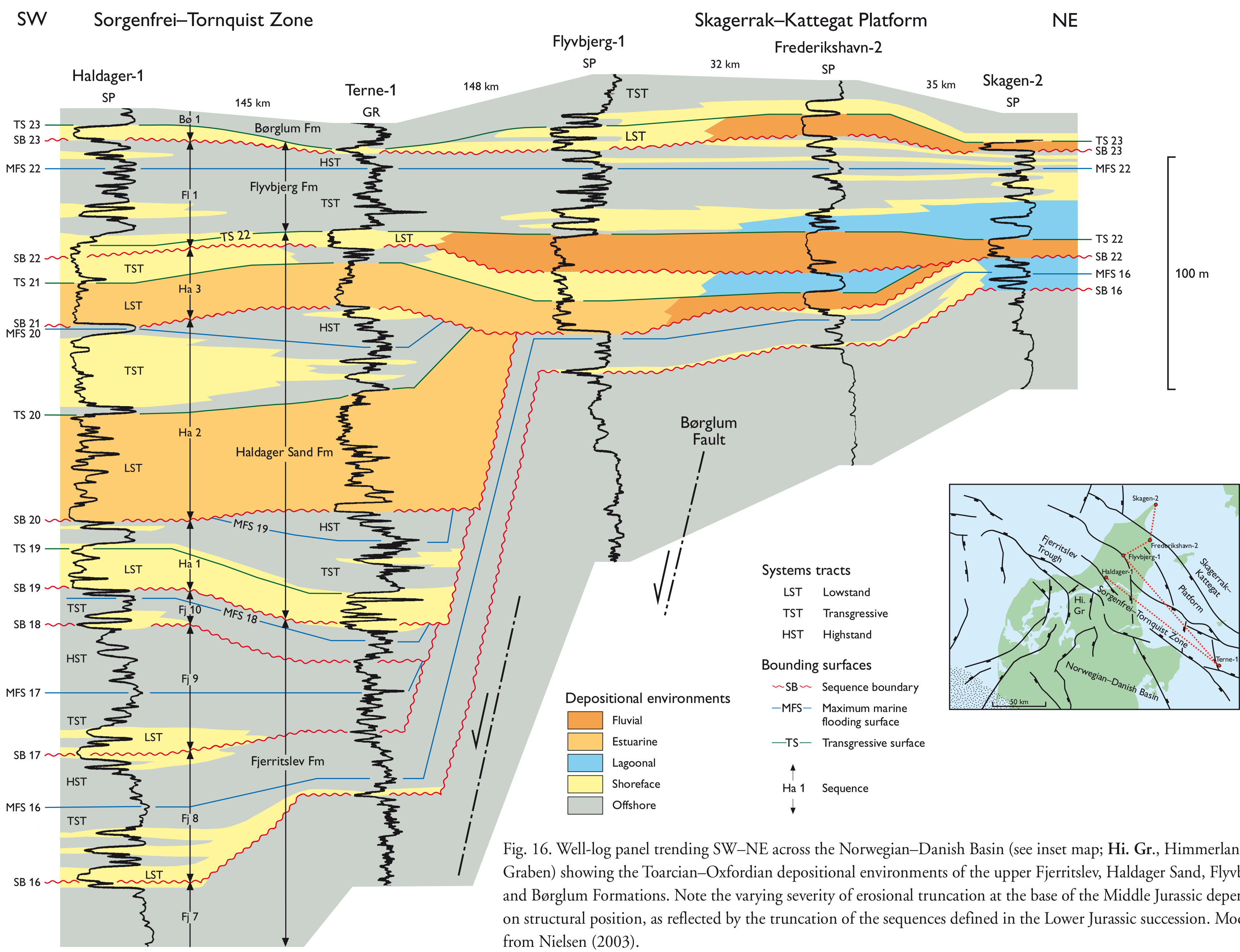


Fig. 16. Well-log panel trending SW–NE across the Norwegian–Danish Basin (see inset map; **Hi. Gr.**, Himmerland Graben) showing the Toarcian–Oxfordian depositional environments of the upper Fjerritslev, Haldager Sand, Flyvbjerg and Børglum Formations. Note the varying severity of erosional truncation 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-

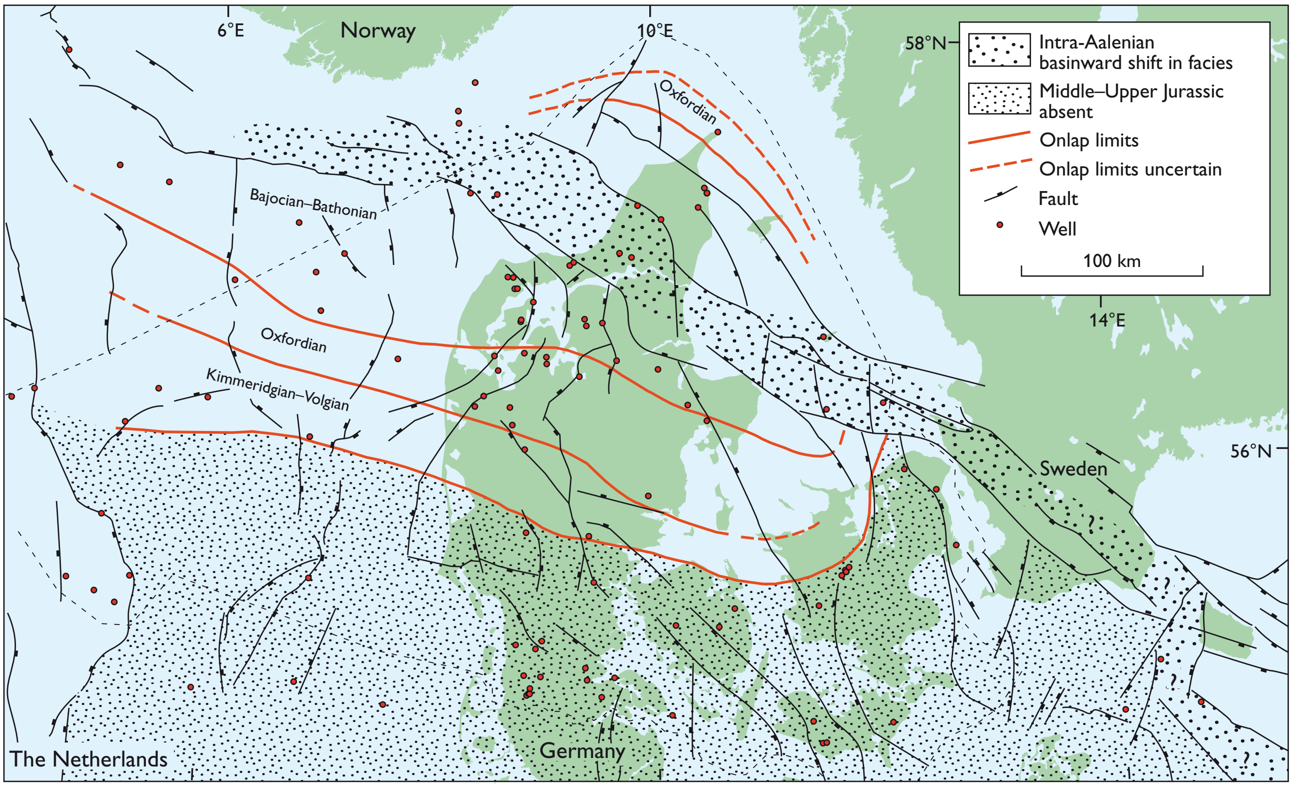


Fig. 17. Map showing the Upper Jurassic – Lower Cretaceous onlap onto the base Middle Jurassic unconformity, indicating the gradual expansion of the depositional area. Modified from Nielsen (2003).

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).