A stratigraphic interpretation of the Oxfordian-Valanginian deposits in the Danish Subbasin

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Abstract

Six sequences are identified in the Upper Jurassic and lowermost Cretaceous Flyvbjerg-, Børglum- and Frederikshavn Formations of the Danish Subbasin. Sequence boundaries and maximum flooding surfaces are interpreted on the basis of log analysis, biostratigraphy and lithology of core samples. Parasequences and parasequence sets are mainly recognized in shallow marine sediments.
The gamma ray and SP logs of the sequences have an overall cyclic character, indicating the presence of upward fining deposits overlain by upward coarsening deposits. A blocky log pattern or an upward decreasing trend lowermost in the sequence represents sand-dominated sediments, and it is interpreted as lowstand deposits caused by forced regression. The overlying interval with upward fining deposits comprise transgressive deposits. The interval between maximum flooding surface and the upper sequence boundary has an upward coarsening trend, and it probably includes the highstand deposits.

Introduction

The marine siliciclastic Upper Jurassic and Lower Cretaceous deposits of the Danish Subbasin (fig. 1) are represented in several deep wells. A sequence stratigraphic study based on petrophysical logs has been carried out. The resolution of conventional seismic sections was demonstrated to be insufficient for a sequence stratigraphic analysis. The log analysis is integrated with biostratigraphic data and with sedimentary facies from core samples to establish chronostratigraphic and genetic relationships between deposits of the marginal and the central parts of the subbasin. The present paper describes the sequence stratigraphy of the Flyvbjerg, Børglum and Frederikshavn Formations in four wells (fig. 2), which represent both shallow marine and fine-grained deeper shelf environments. Sequences, parasequence sets and parasequences are identified and correlated.
Some stratigraphic analyses have previously been published, e.g. lithology and chronostratigraphy by Sorgenfrei & Buch (1964), and biostratigraphy by Davey (1982). The lithostratigraphy was described by Larsen (1966) and supplementary details are found in Michelsen (1978, 1989) and Michelsen & Nielsen (1991).

Geological setting

The Danish Subbasin is a part of the northwest-southeast oriented Norwegian-Danish Basin, which is considered as an epicontinental basin. It is bordered to the southwest by the Ringkøbing-Fyn High (fig. 1). To the northeast the subbasin is bordered by the Fennoscandian Border Zone, including Sorgenfrei-Tornquist Zone and the Skagerrak-Kattegat Platform. To the west the Danish Subbasin is bordered by the middle Mesozoic Lista Nose. The Danish Subbasin experienced only minor tectonic activities since the early Mesozoic (EUGENO-S, 1988).
The Danish Subbasin developed during the Triassic, and more than 5 km of mostly continental sediments were accumulated (Bertelsen, 1980). The rate of subsidence decreased during the Late Triassic, and mainly marine sedimentation dominated the area (Michelsen, 1978; Bertelsen, 1980). A Middle Jurassic tectonically controlled local subsidence is indicated within the Sorgenfrei-Tornquist Zone (Michelsen & Nielsen, 1991). During the Late Jurassic and the Early Cretaceous the tectonic activity decreased to a minimum as a conse-

quence of the cooling of the lithosphere (Vejbæk, 1990). The Late Cretaceous to Early Tertiary tectonic inversion of this zone are described by Liboriussen et al. (1987) and EUGENO-S (1988).

Three cycles of continental/shallow marine to marine sedimentation took place during the Rhaetian-Early Jurassic, Middle-latest Jurassic, and latest Jurassic-Early Cretaceous times (Larsen, 1966). The marine influence in the Danish Subbasin increased during the Cretaceous period and culminated during the Late Cretaceous.

Parts of the second and third cycles, reflecting the Late Jurassic and earliest Cretaceous basin development, are theme of this paper. At the beginning of the Late Jurassic shallow marine sedimentation dominated in the Danish Subbasin (Flyvbjerg Formation). The succeeding deeper marine sedimentation (Børglum Formation) took place during the latest Oxfordian and the Kimmeridgian. The marine dominans continued in the western-central parts of Danish Subbasin through the remaining part of the Jurassic and through most of the Early Cretaceous (Vedsted Formation). In the northern marginal part of the subbasin, shallow marine silt and sand (Frederikshavn Formation) were deposited during the Late Kimmeridgian to Valanginian, and deeper marine conditions (Vedsted Formation) occurred in the remaining part of the Early Cretaceous (Michelsen, 1978, 1989).

Materials and methods

The interpretation of lithology and sedimentary facies is based on the petrophysical logs and cuttings and core sample descriptions from the Frederikshavn-1, Børglum-1, Haldager-1 and Hyllebjerg-1 wells. The gamma ray, SP, resistivity and sonic logs are used, and occasionally also the neutron-density logs. Cores from the Frederikshavn-1 well were studied at selected intervals to support the log interpretation, and to describe changes in sedimentary facies across some sequence stratigraphic surfaces. Interpretation of the depositional environment is supported by biostratigraphy, which also is used to establish the chronostratigraphic subdivision. Individual depositional systems are grouped into depositional sequences, bounded by unconformities and their correlative conformities in accordance with the concepts of Mitchum et al. (1977) and Van Wagoner et al. (1988; 1990).

Sequence stratigraphy

The Flyvbjerg Formation is dominated by shallow marine (and non-marine?) siltstone and claystone, and the Børglum Formation by claystone deposited in a deeper shelf situation. The Frederikshavn Formation comprises of sandy, silty and clayey deposits, reflecting repeated changes from near coastal to fully marine conditions (Larsen, 1966; Michelsen, 1978).

A sequence stratigraphic interpretation of the three formations is presented in figure 2, which includes the Frederikshavn-1, Børglum-1, Haldager-1 and Hyllebjerg-1 wells. The Frederikshavn-1 well represents a marginal situation in the basin, and Hyllebjerg-1 the central part of the basin. The two other wells are located in an intermediate position, which occasionally during the Late Jurassic-earliest Cretaceous is dominated by near coastal environments (Larsen, 1966).

The observed cyclic character of these siliciclastic sediments is the basis for recognition of candidates for sequence boundaries and maximum flooding surfaces. Parasequences and parasequence sets are identified in the individual wells, mainly on the basis of the gamma ray and SP logs.

Flyvbjerg and Børglum Formations

The Flyvbjerg Formation is probably separated from the underlying Haldager Sand Formation by a regional hiatus. The top of the Haldager Sand Formation is of Late Callovian age (or younger), and the base of the Flyvbjerg Formation is of Middle to Late Oxfordian age, being youngest in northern marginal part of the subbasin (Poulsen, 1993). The boundary between the two formations is here suggested as the lower boundary of the lowermost sequence, S-1 (fig. 2).

The log patterns of the Flyvbjerg Formation have an upward coarsening trend, reflecting a transition from claystone lowermost to silt- and sandstone uppermost. This trend is best developed in the central parts of the Danish Subbasin. The upward coarsening section probably reflects a basinward migration of the coastline, and may be interpreted as the lowermost lowstand deposits of sequence S-1.

The base of the overlying Børglum Formation is of Early Kimmeridgian age in the central part of the subbasin (Hyllebjerg-1), but seems to get younger (Late Kimmeridgian age) towards the margin of the subbasin (Poulsen, 1993). The fully marine claystones of the formation probably represent the transgressive conditions following the shallow marine prograding deposits of the Flyvbjerg Formation, and the lower boundary of the Børglum Formation is regarded as a major transgressive surface. The Børglum Formation can be divided into two parts of almost equal thickness. The lower part is characterized by upward increasing gamma ray and decreasing resistivity values, indicating an upward increasing clay content (fig. 2). Upward decreasing gamma ray values characterize the upper part of the formation, reflecting an increasing silt/clay ratio, which is probably to be a result of shallowing conditions. This interpretation is also supported by an upward increasing ratio between terrestrial and marine palynomorphs (Andersen, 1988). The lower and upper parts of the Børglum Formation are separated by a level with maximal marine conditions, that easily can be correlated between all wells (fig. 2). This level is interpreted as a maximal marine flooding surface.

The upper boundary of sequence S-1 coincides with the boundary between the Børglum and Frederikshavn Formations, which will be described below.

Frederikshavn Formation

The gamma ray and SP logs of the Frederikshavn Formation show a pronounced cyclic character, representing changes from near coastal coarse-grained deposits to fully marine clayey facies. The formation is here subdivided into five depositional sequences: The Late Jurassic S-2, S-3 and S-4 sequences and the Early Cretaceous S-5 and S-6 sequences (fig. 2).

The lower boundary of sequence S-2 coincides with the boundary between the Børglum and Frederikshavn Formations. The formation boundary is characterized by an upward decreasing gamma ray trend and an abrupt increase in sonic velocities, reflecting a change to silty and sandy deposits. A basinward shift in facies across the boundary is also seen in a core from the Frederikshavn-1 well (fig. 3). Biostratigraphic data and an abrupt decrease in the gamma ray log from the Sæby-1 well indicate the presence of a hiatus at this boundary, but the hiatus seems to disappear towards the central part of the subbasin. The sequence boundary is of Early Volgian age and is suggested to be synchronous throughout the subbasin by Poulsen (1993).

The gamma ray and SP curves of sequence S-2 reflect upward fining deposits overlain by upward coarsening deposits. The maximum flooding surface is located at the highest gamma ray values, which in the central part of the subbasin (Hyllebjerg-1) are found close to the lower sequence boundary (fig. 2). The interval between the lower boundary and the maximum flooding surface can not be interpreted clearly in the context of lowstand and transgressive deposits. However, an upward coarsening trend occurs lowermost in the Frederikshavn-1 well, indicating the presence of prograding lowstand deposits in the marginal part of the subbasin. The interval above the maximum flooding surface shows a pronounced upward shift to coarse-grained facies, which is interpreted as prograding conditions (fig. 2).

Sequence S-2 is overlain by two thin sand-dominated intervals, characterized by a blocky SP log pattern in the Børglum-1 and Haldager-1 wells (fig. 2). These two intervals are identified as sequences S-3 and S-4, and interpreted as stacked lowstand deposits situated in an intermediate position of the basin. Sequence S-3 seems to be thinning in the landward direction, and a transgressive-regressive succession following the lowstand deposits is not recognized in the present well data, but could be present northeast of the study area (in the landward direction) or it may have been removed by erosion. A Middle Volgian age is assigned to deposits at the lower boundary of sequence S-3 marginally in the subbasin (Sæby-1). Equivalent deposits is dated slightly younger in the Frederikshavn-1 well (Andersen, 1988).

The lower boundary of sequence S-4 is dated to the Early Portlandian (latest Middle Volgian) in Haldager-1 (Davey, 1982) and Middle (or Late) Volgian in the marginal Sæby-1 well. The log features of sequence S-4 changes in the landward direction from the blocky pattern to a cyclic pattern (Frederikshavn-1 in fig. 2). The sequence comprises here two parts separated by a possible maximum flooding surface. An increased content of glauconite is described from the interval comprising this surface (Larsen, 1966). The interval above the maximum flooding surface in Frederikshavn-1 comprises two upward decreasing gamma ray trends (parasequences), and is characterized by overall upward coarsening deposits (figs 2 and 4). Frequent occurrences of wood debris, decreasing content of glauconite and a higher ratio of terrestrial/aquatic palynomorphs (Andersen, 1988) in this upper part of sequence S-4 probably reflects a basinward migration of the lithofacies.

The lower sequence boundary of the overlying sequence S-5 is of latest Early Portlandian age (Davey, 1982). The deposits immidiately above the sequence boundary in the Haldager-1 well is possible of Late Portlandian age (Davey, 1982).

The gamma ray pattern of sequence S-5 shows a cyclic character with an increasing trend followed by a decreasing trend. The maximum flooding surface is located in the interval with the highest gamma ray values, which is a clay-dominated deposit. The interval below the maximum flooding surface in the Børglum-1 and Haldager-1 wells includes two sand/silt sections interbedded by a thin clayey interval. The lower sand section may be interpreted as lowstand deposits, which is not present in the more proximally located Frederikshavn-1 well, and the upper sand may represent the basal part of the transgressive deposits. The Portlandian-Ryazanian transition is found between the two sandy sections in the Haldager-1 well (Davey, 1982). Time equivalent transition is also found immidiately above the sequence boundary in the Frederikshavn-1 well (Andersen, 1988) and in the nearby Sæby-1 well.

The clay-dominated interval with the maximum flooding surface of S-5 is followed by upward coarsening deposits. The sandy/silty sections become thicker and more coarse-grained upwards; and more coarse-grained sediments occur in the Børglum-1 well than in Haldager-1. This part of the sequence is interpreted as a succession of prograding parasequence sets. The interval is terminated by a sudden decrease in gamma ray, indicating a basinward shift of lithofacies, which is interpreted as the boundary between sequence S-5 and S-6. This sequence boundary is of Valanginian age (Davey, 1982).

Sequence S-6 comprises a lower coarse-grained part and an upper fine-grained part. The log pattern of the lower part has a blocky appearance in the Frederikshavn-1, Børglum-1 and Haldager-1 wells (fig. 2). In Frederikshavn-1 the blocky interval is succeeded by increasing gamma ray values, corresponding to an upward increase in the content of clay and glauconite (Larsen, 1966). The palynoform assemblages reflect an increasing distance from coast (Andersen, 1988). The increasing gamma ray trend is separated from the upper part by a gamma ray maximum, which is interpreted as the maximum flooding surface. The upper part is thickest in landward direction (Frederikshavn-1), and it is more fine-

grained and comprises a higher content of shelf fossils than below the maximum flooding surface (Andersen, 1988). The interval above the maximum flooding surface thins in basinward direction, as it also was the case in sequence S-4 (fig. 2).
The upper boundary of sequence S-6 is located uppermost in the Frederikshavn Formation in the Børglum-1 and Haldager-1 wells and in the lower part of the overlying Vedsted Formation in the Frederikshavn-1 well. In Børglum-1 and Haldager-1, the boundary is placed at the base of a blocky log pattern, which represents coarse-grained deposits, interpreted as a basinward shift in lithofacies. If our sequence stratigraphic interpretation is correct it implies that the Frederikshavn/Vedsted Formation boundary is diachronous. The chronostratigraphic significans of our interpretation can hardly be confirmed by the available biostratigraphy, which indicates a Middle or Upper Valanginian age. Further biostratigraphic analyses are necessary to evaluate the validity of our interpretation of the transition from sequence S-6 to S-7.

Conclusion

The Upper Jurassic to lowermost Cretaceous Flyvbjerg, Børglum and Frederikshavn Formations are subdivided into six sequences, and the presence of parasequences and parasequence sets is indicated by log interpretation in a number of wells and by lithological analysis of core samples from the Frederikshavn-1 well. The chronostratigraphic significance of the sequences is supported by biostratigraphy in the tree wells: Frederikshavn-1, Haldager-1 and Hyllebjerg-1.
Sedimentary cycles interpreted as parasequences and parasequence sets are mainly recognized in the shallow marine sediments. More basinward the silt and sand supply is reduced, and a parasequence interpretation is difficult to perform on the basis of logs.
It has been difficult to carry out a systems tract interpretation (sensu Posamentier et al., 1988), because of the large distances (30-50 km) between the wells and of the fact that the available seismic sections were not useable. However, the cyclic log feature of the sequences is interpreted as a succession of upward fining deposits overlain by upward coarsening deposits. The blocky log pattern and the upward coarsening trend lowermost in the sequences represent sand-dominated deposits, which are regarded as lowstand deposits caused by forced regression in a epicontinental setting (Posamentier et al., 1992). The overlying interval with upward fining deposits may comprise transgressive deposits, and the gamma ray maximum is suggested to represent the maximum flooding surface. The interval between this surface and the upper sequence boundary is characterized by upward coarsening deposits, especially in sequences S-2 and S-5 and it may include highstand deposits.

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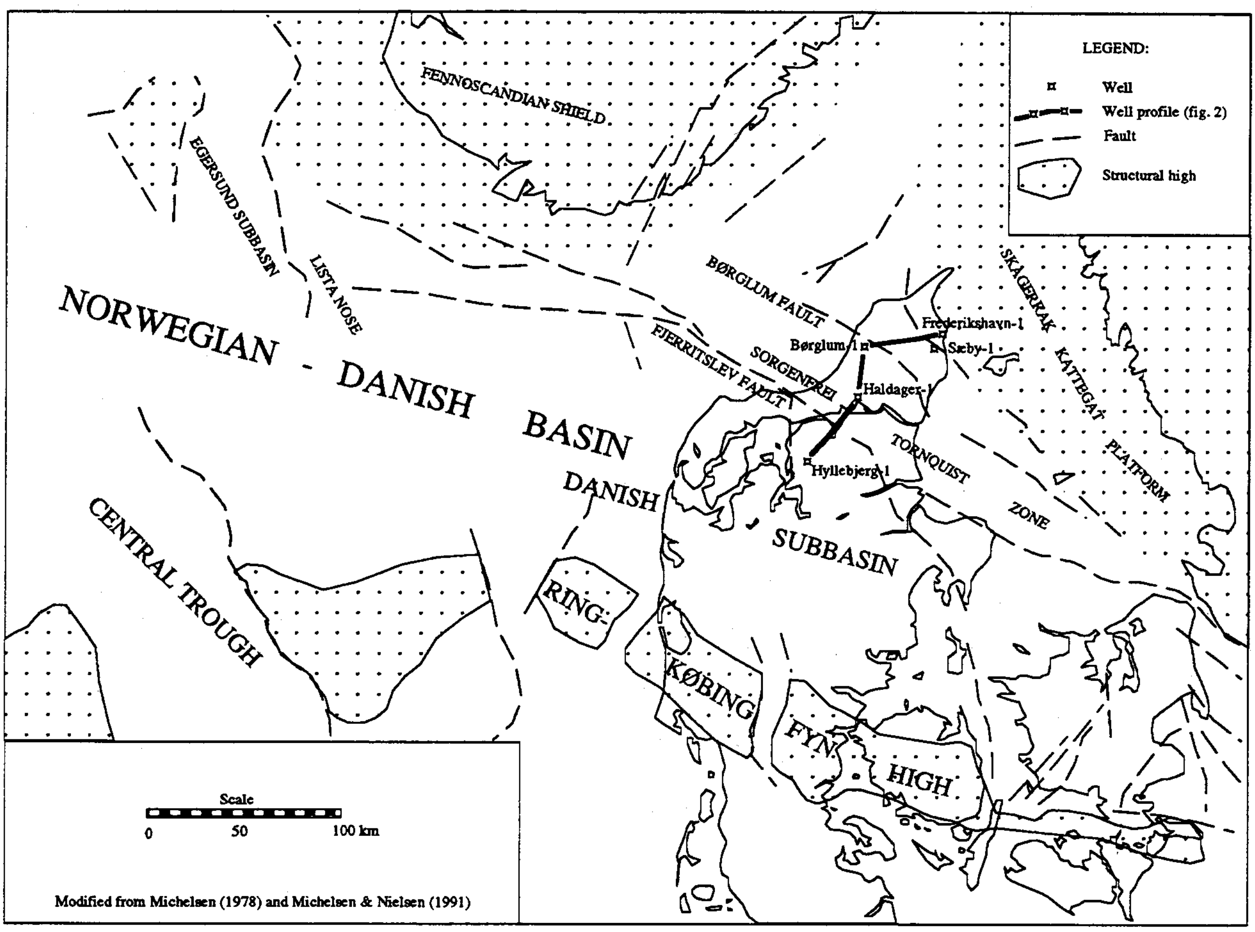


Fig. 1 Structural map of the Norwegian - Danish Basin (including the Danish Subbasin). Locations of wells mentioned in the text are indicated.

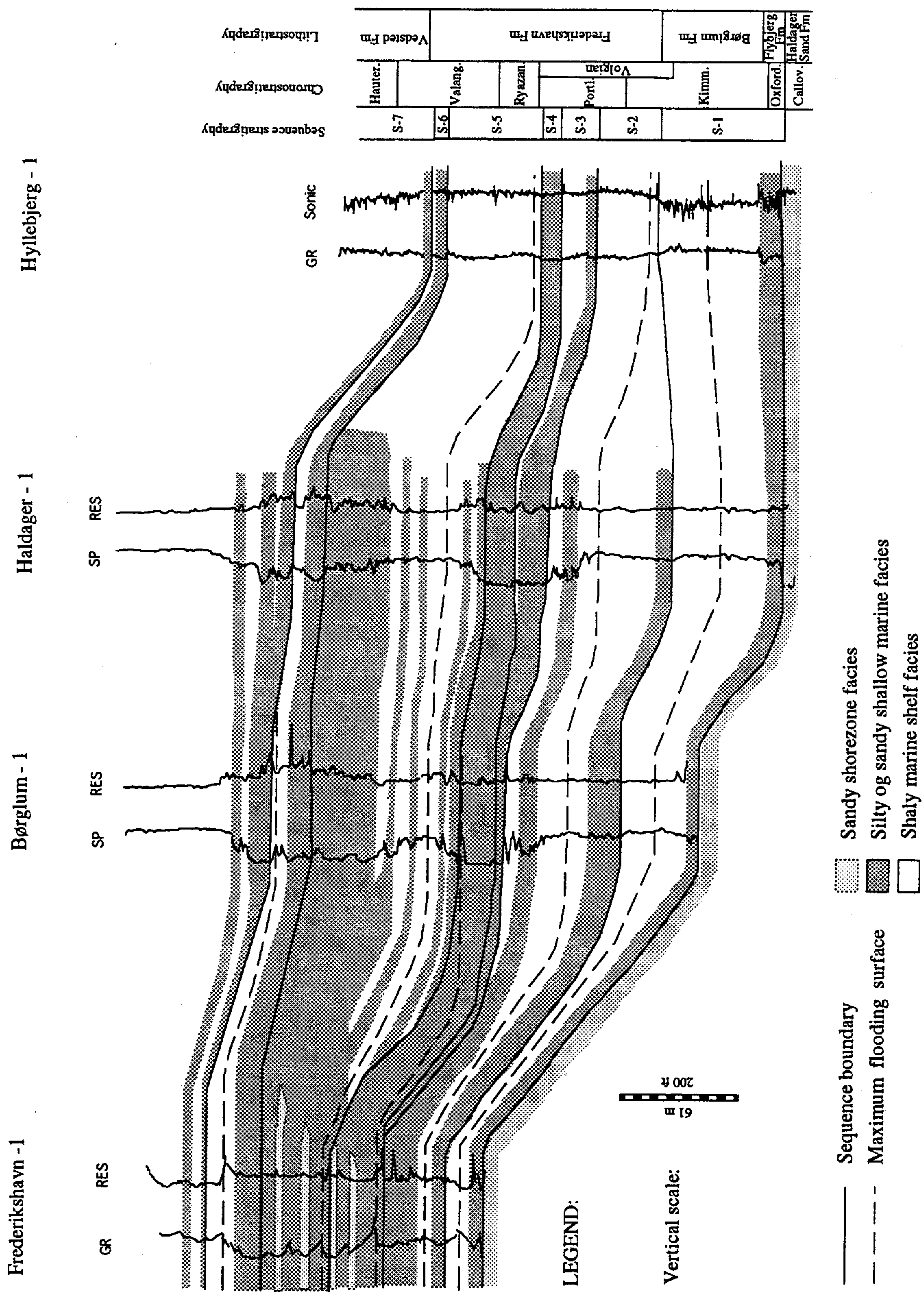
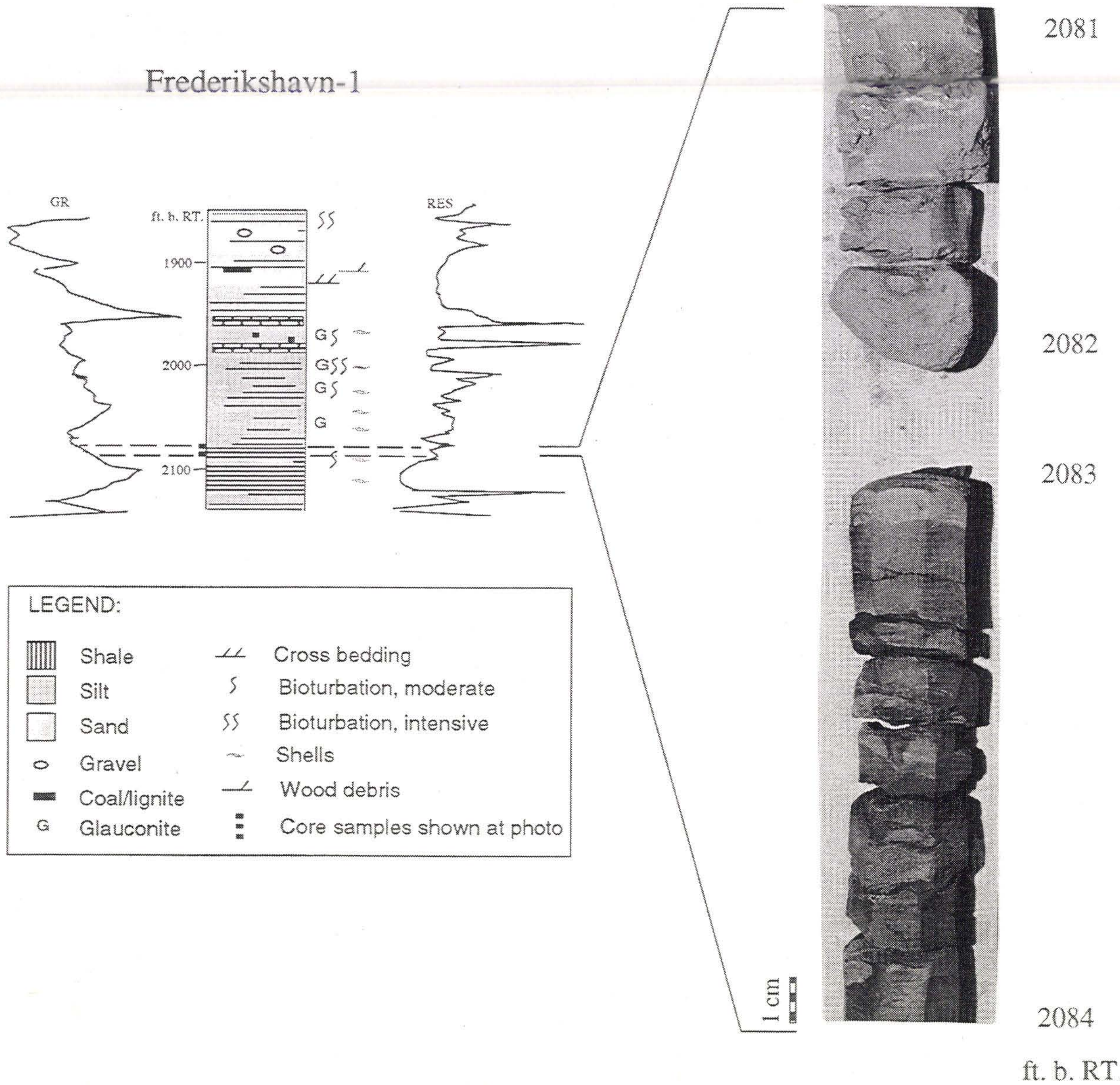


Fig. 2 Sequence interpretation of the Flyvbjerg-, Børglum- and Frederikshavn Formations in four wells from the marginal and central parts of the DanishSubbasin. See fig. 1 for well locations.



Core description:

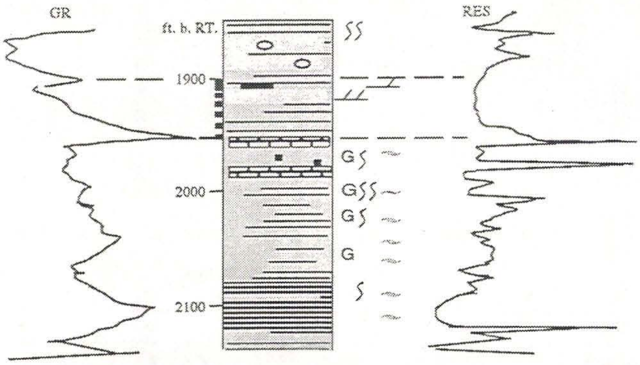
2081-2082 ft. b. RT:
Light grey to light green silt interbedded with thin shales.
More greenish glauconitic sediments and more bivalve debris, than the core samples below.

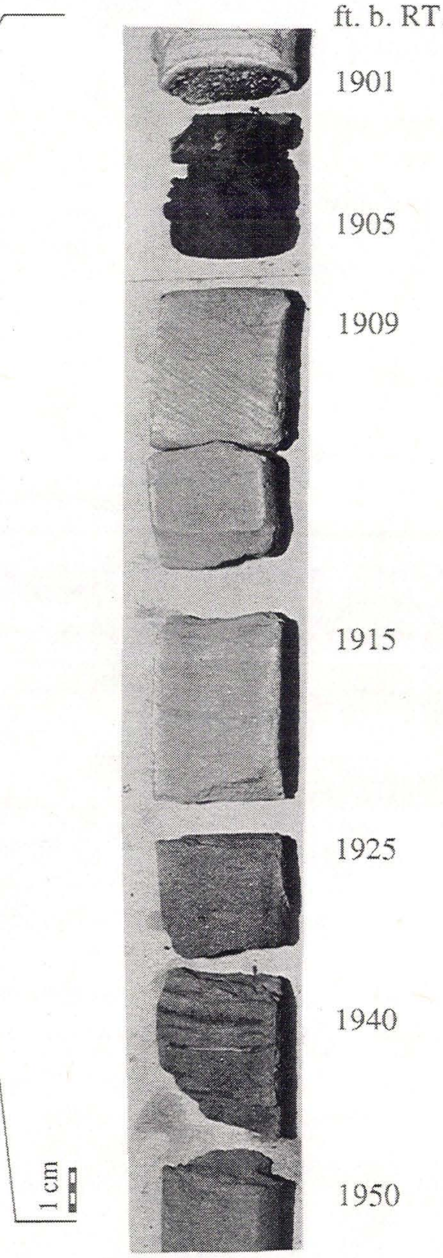
2083-2084 ft. b. RT:
Dark grey shale and claystone, interbedded by thin light grey clayey fine silt layers (thickness: 0,5-1 cm). The claystone is consolidated and contains some light deform areas, inpartikular just above the clayey fine silt layers and some small thin bivalve shells.

Interpretation of depositional environment:

The lower clayey part seems to be bioturbated. The relative dark clayey facies with small thinshelled bivalves indicates a marine shelf environment. The increasing silt content and increasing bed thicness reflects a relative abrupt change to shallow marine conditions.
Notice the horisontal boundary between the dark shelf sediments and the lighter silt just below 2083 ft. It is considered to be the first regional basinward faciesshift, indicating a more close position of the coast.

Fig. 3 Description of lithology and interpretation of depositional environment in core samples from 1901-1950 ft. b. RT. in the Frederikshavn-1 well.





LEGEND:

- Shale
- Silt
- Sand
- Gravel
- Coal/lignite
- G Glauconite
- Cross bedding
- Bioturbation, moderate
- Bioturbation, intensive
- Shells
- Wood debris
- Core samples shown at photo

Core description:

1901 ft. b. RT:
Light greyish green fine-grained glauconite sand interbedded with thin claystone.

1905 ft. b. RT:
Dark grey brown coal/lignite and shale with silt and wood debris.

1909 ft. b. RT:
Light grey green fine- and medium-grained sandstone interbedded by thin grey shale.
The sandstones (1909-1915 ft) is mostly thicker than in the interval below and crossbedded (20-45°).

1915 ft. b. RT:
Light green micacous coarse-grained siltstone interbeded by shale.
Core pieces with siltstone is thinner than above and contains in part planar bedded sandstone.

1925 &1940 ft. b. RT:
Grey to red brown silty shale og siltstone.
Where it is reddish it seems more consolidated and sometimes it is ionstone.
The grey green fine grained siltstone resamples the core sample at 1915 ft, but is more fine-grained.

1950 ft. b. RT:
Olive greenish glauconite silt- and fine-grained sand.

Interpretation of depositional environment:

The high content of greenish glauconite in the lower and upper part of the succession indicates with the silty sediments shallow marine conditions.
From bottom to the top the content of glauconite decreases, and the grain size and the thickness of the fine- and medium-grained sandstone increases and crossbedding can be seen.
This indicates upward increasing (wave-) energy level, that could be due to a relative lowering of sealevel or increased sediment supply.
This progradation is terminated by lagunal shale.
The succession probably reflects a prograding beach- or barrier-island environment, drowned and succeed by shallow marine glauconitic silt- and fine-grained sandstone.

Fig. 4 Description of lithology and interpretation of depositional environment in core samples from 2081-2084 ft. b. RT. in the Frederikshavn-1 well.