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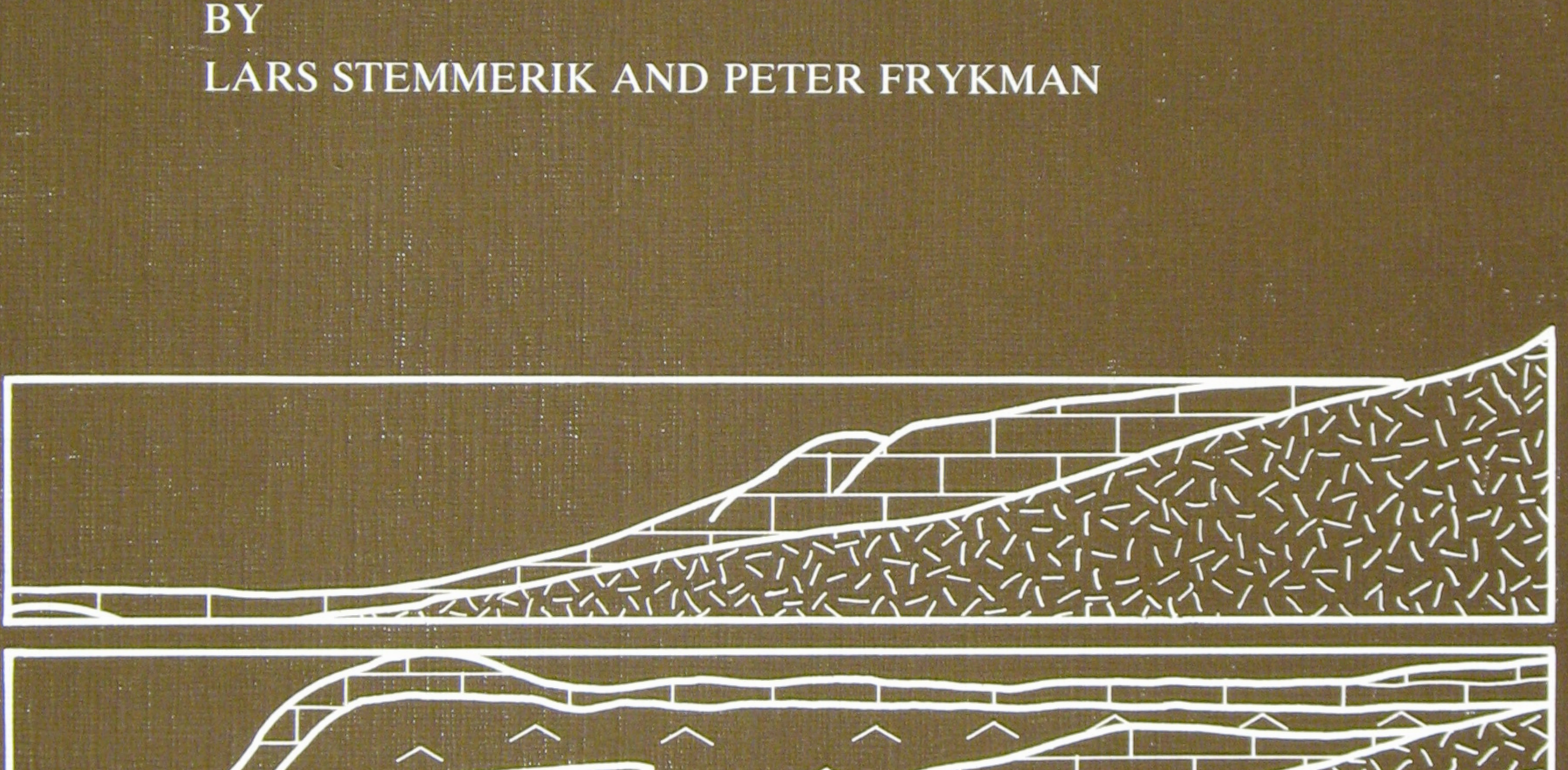

Danmarks Geologiske Undersøgelse · København 1989

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Key words:
Zechstein, Denmark, Sedimentology, Stratigraphy, Evaporites, Carbonates.

Vignette:
Schematic section through stages in the development of the Ca-2 carbonate platform.

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Preface

This report summarizes part of a research project entitled »Diagenesis and porous system in Danish Zechstein carbonate reservoirs«. This project, partly financed by the EEC (contract No. EN3C/0030-DK (MB)), extended from April 1986 to April 1989. Leadership of this EEC project at DGU was undertaken by Ole Winther Christensen; Erik Nygaard lead the project during his absence. From April 1987 additional project leading was undertaken by Peter Frykman. The project is a continuation of earlier investigations concerning the Zechstein deposits, as reported by Stentoft & Nygaard (1985) in connection with an EFP-84 project financed by the Danish Ministry of Energy.

The purpose of the present project was to document the sedimentary and diagenetic evolution of the carbonates, especially with respect to porosity development. Emphasis was placed on two important aspects of the rock characteristics – sound velocity and pore geometry, and correlation between the different parameters was attempted.

The main results of these sedimentological and diagenetic investigations have been reported previously by Stemmerik, Frykman, Christensen & Stentoft (1987) and in DGU Internal Reports by Stentoft & Nygaard (1986) and Stemmerik, Frykman & Stentoft (1986). The diagenesis will be treated in detail by Stentoft (in press) and is accordingly only covered briefly in this report.

Contents

Abstract

The Upper Permian Zechstein succession of southern Jylland, Denmark, is composed of a cyclic repetition of carbonate, anhydrite and salt, and includes four main carbonate units: Ca-la, Ca-lb, Ca-2 and Ca-3.

The stratigraphy and log-correlation in the southern Jylland area is outlined and compared to other areas. Descriptions of facies and interpretation of depositional models for the four carbonate units are presented. The depositional system comprised a shelf with marginal sabkha evaporites and carbonates; the shelf underwent evolution from a ramp-like to a platform configuration. This evolution is seen as the result of the interplay between evaporite and carbonate sedimentation. Accumulation of sulphate evaporites during Z-1 times produced a sediment body with a platform morphology. Z-2 carbonate deposition further enhanced the platform configuration, with consequent development of a marked zonation of facies according to energy level. Later in Z-2 time the platform – basin system suffered demise as the basinal areas were filled with halite and during the remaining period of basinal history shallow water conditions prevailed throughout the area.

Introduction

During the early 1950's and 1980's the Zechstein carbonates in southern Jylland formed a major target in the exploration for hydrocarbons within onshore Denmark. To date, no commercial production has been established, but several wells had hydrocarbon shows and were tested (Stemmerik et al. 1987). Recently, three of the exploration wells drilled in southern Jylland by Dansk Boreselskab A/S were released. Material from these wells, from five old wells drilled by DAPCO in the 1950's and from released seismic surveys, form the basis for this study of the Zechstein succession in southern Jylland.

During Zechstein time southern Jylland was situated along the northern margin of the NW German Zechstein Basin (figs. 1, 2). The investigated wells represent a transect from the northern marginal marine areas along the Ringkøbing-Fyn High to the southern basinal areas found in the Tønder Trough (figs. 2, 3). However, the majority of the recent exploration wells were drilled close to the platform margin.

Cored material mainly originates from carbonate intervals within the succession. Therefore, the detailed sedimentological investigations presented here are restricted to the carbonate units of the Zechstein 1 – 3 cycles (Ca-la, Ca-lb, Ca-2 and Ca-3). Sedimentological models for each of the carbonate units are presented and compared to models developed elsewhere in the basin. Previous presentation of the sedimentological models (Stemmerik et al. 1987) lacked detailed facies descriptions; these details are presented here in addition to a more highly developed interpretation of depositional environments and the evolution of the depositional system.

Regional Setting

The Zechstein sequence is a complex of evaporite and carbonate rocks of Late Permian age, which underlies a substantial area of the North Sea and Northwest Europe (fig. 1).

The extension of the Zechstein Basin north of latitude 59° N is poorly established. Upper Permian carbonates in East Greenland (Maync 1961, Surlyk et al. 1986) and diapirs in the Norwegian Troms Basin (King 1977) indicate that carbonate and evaporite sedimentation extended to about 75° N. However, the cyclic five fold division recognised in the NW European Zechstein basins does not occur in this region, suggesting a northern limit of the Zechstein Basin *sensu stricto* not far north of 59° N.

In NW Europe, the Zechstein succession occupies two E-W trending subbasins partly separated by the Mid North Sea - Ringkøbing-Fyn High (Ziegler 1981). Much of the Ringkøbing-Fyn High remained exposed throughout Zechstein times. Thick salt occupies the basin centres, whereas carbonate and anhydrite are more important around the edges and over the Mid North Sea High.

The northern salt basin stretches from the Firth of Forth, Scotland across the North Sea to northern Denmark. It is fairly well delineated in seismic sections, which show the Zechstein sequence to be over 2000 m thick in the Norwegian-Danish Basin (Taylor 1981), but relatively little is known about the sequence as it is below current drilling depths. The southern salt basin extends from eastern England across the Netherlands and Germany to Poland and western Russia, and is well known as a result of the search for hydrocarbons and minerals.

During Zechstein time southern Jylland was situated along the southern slope of the Ringkøbing-Fyn High, which at that time formed the northern margin of this southern salt basin known as the NW German Basin (figs. 1, 2). Major structural elements which may have influenced sedimentation are the Ringkøbing-Fyn High, Arnum Block, Rødekro High, Tønder Trough, and Brande Trough (fig. 2).

The complex of blocks and north-south trending transecting troughs making up the Ringkøbing-Fyn High was probably formed during Stephanian-Autunian times as a result of late Variscian right lateral wrench tectonics (Ziegler 1982). These Late Carboniferous to Early Permian wrench movements were associated with the development of a complex array of conjugate shear faults and pull-apart structures. Rapid subsidence and extrusion of locally thick Lower Rotliegendes volcanics were especially marked in northern Germany and Poland, where it was probably associated with wrench movement along the Tornquist-Teisseyre fault system (Taylor 1984). This wrench fault became largely inactive by the onset of the Saxonian (U. Rotliegendes), whereafter the northern and southern Permian basins began to subside.

The subsiding basin can be viewed as a huge intracontinental crustal depression. Prior to the Late Permian (Zechstein) transgression, the area formed an enormous inland desert. After flooding, the basin was still an area of very limited clastic sediment supply and therefore became filled by carbonates and evaporites.

The depth of the crustal depression at the time of transgression is difficult to estimate. From morpholog-

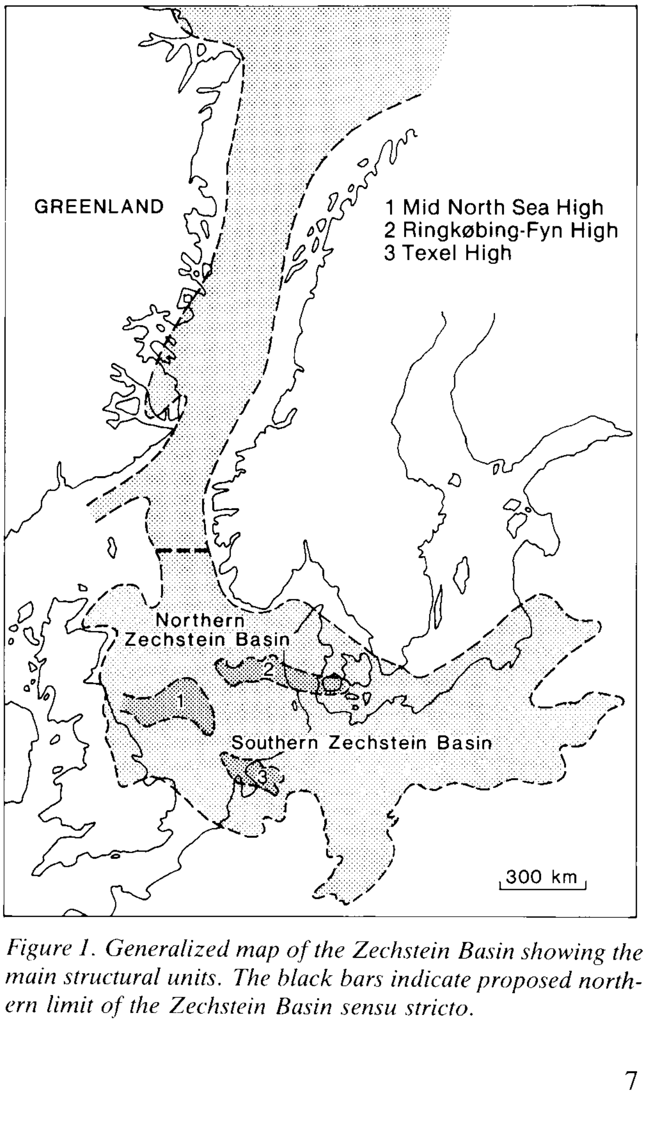


Figure 1. Generalized map of the Zechstein Basin showing the main structural units. The black bars indicate proposed northern limit of the Zechstein Basin sensu stricto.

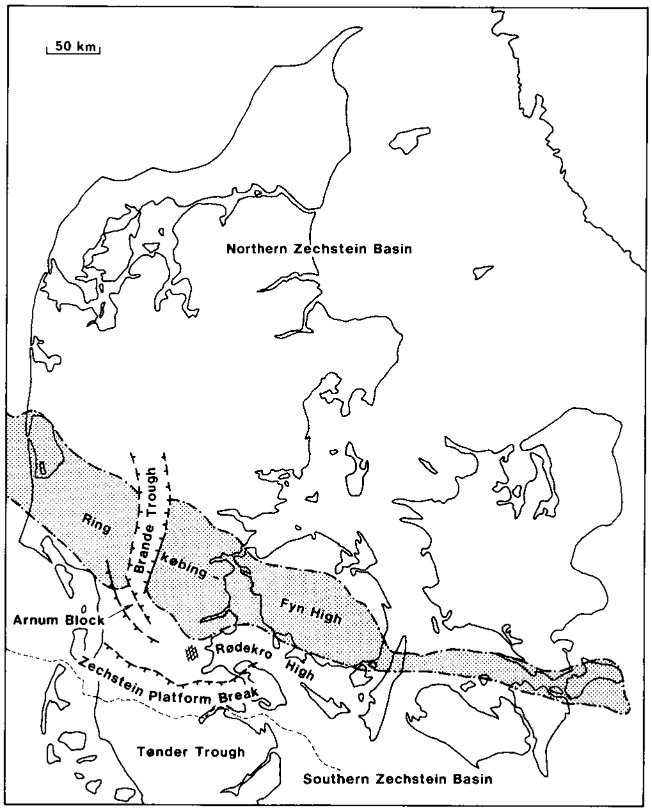


Figure 2. Structural outline of southern Denmark. Based on Baartman, (in Rasmussen, 1978).

ical features like Permian aeolian sand dunes and palaeohills overlain by the initial Zechstein deposits, Smith (1979) has estimated the relief to be at least 200 m.

In southern Jylland, Zechstein sediments have not been encountered in wells drilled on the Ringkøbing-Fyn High and Rødekro Block (Bertelsen 1980), and the Zechstein sequence in the Arnum-1 well on the Arnum Block (fig. 2) is less than 100 m thick. The thickness of the sequence in the platform area is 470–530 m increasing to 650 m in the basin further to the south (figs. 3, 4). The fault system defining the northern margin of the Tønder Trough appears locally important dividing the area south of the Ringkøbing-Fyn High into a northern carbonate-anhydrite dominated platform area and a southern salt dominated basin (fig. 4). This division was particularly well-developed during late Z-1 and early Z-2 times (fig. 4). Some of the relief between the platform and the basin may have resulted from synsedimentary movements along the fault system.

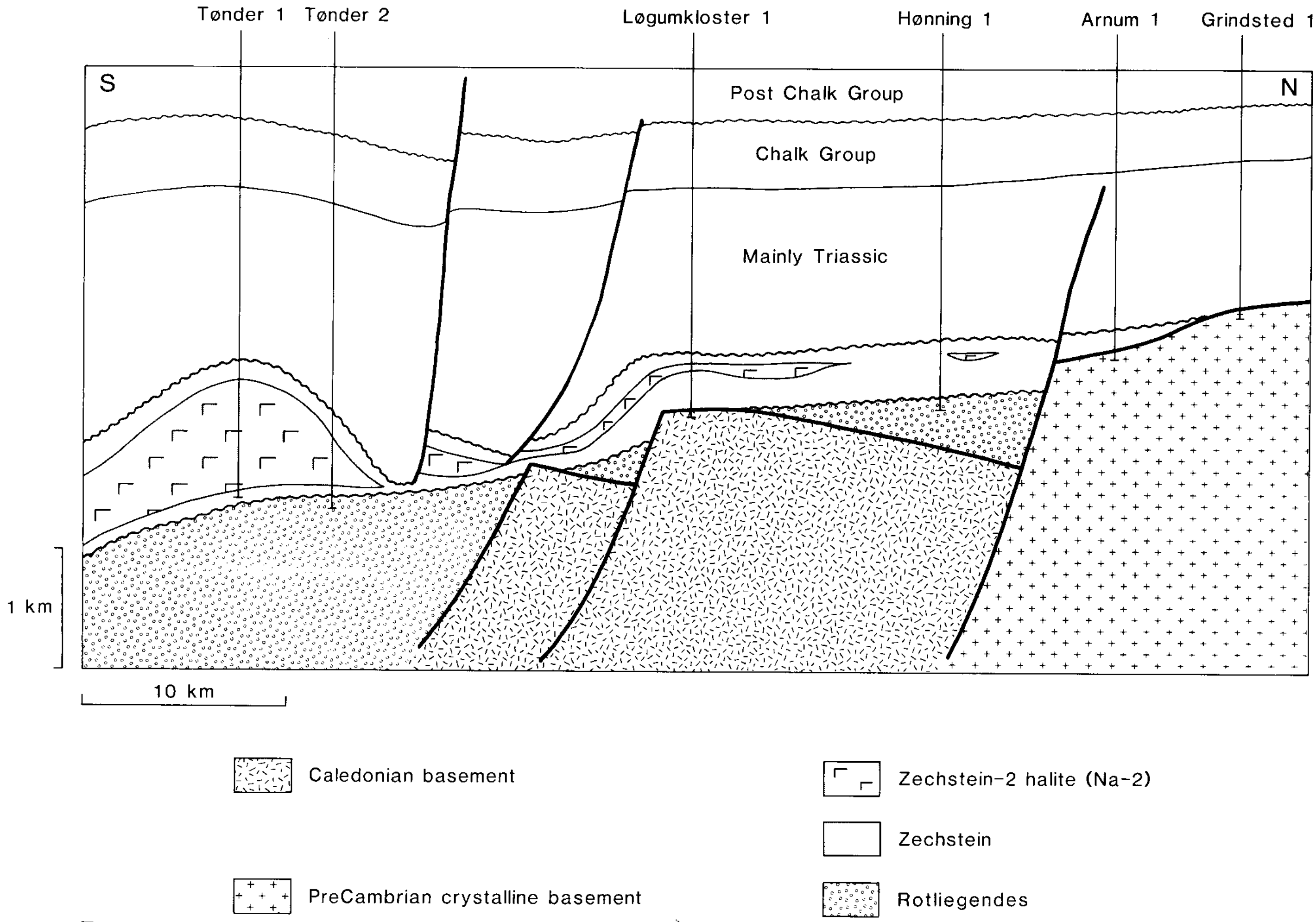


Figure 3. Simplified north-south cross section of the subsurface geology in southern Jylland. Where necessary the wells are projected onto the schematic section, drawn from seismic line 7801. (Modified from Thomsen et al. (1987)).

However, most of the relief seems to have been caused by differential sedimentation which greatly enhanced the distinction between the platform and the basin. Evaporite sequences, which are thick on the platform and thin into the basin, created considerable relief especially during Z-1 time. Deposition of the succeeding Ca-2 carbonates was therefore influenced significantly and widely different carbonate facies accumulated in the platform and basinal settings. This type of upward progradation of platform evaporites has been described by Sannemann, Zimdars & Plein (1978) and Colter & Reed (1980) from elsewhere in the Zechstein basin.

During Z-2 times halite gradually filled the basinal areas in the Tønder Trough and during the remaining part of the Zechstein, shallow water conditions occurred throughout the investigated area.

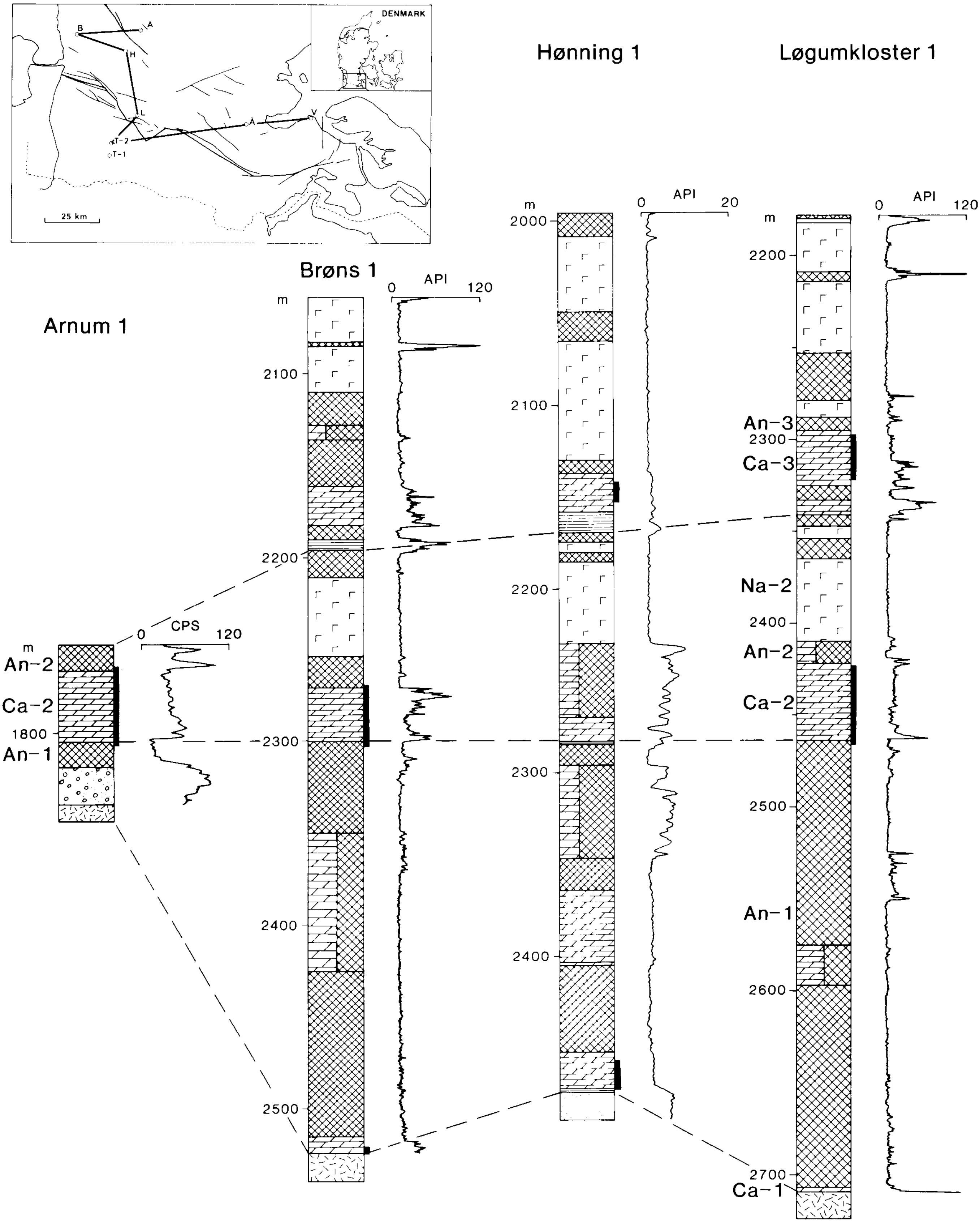
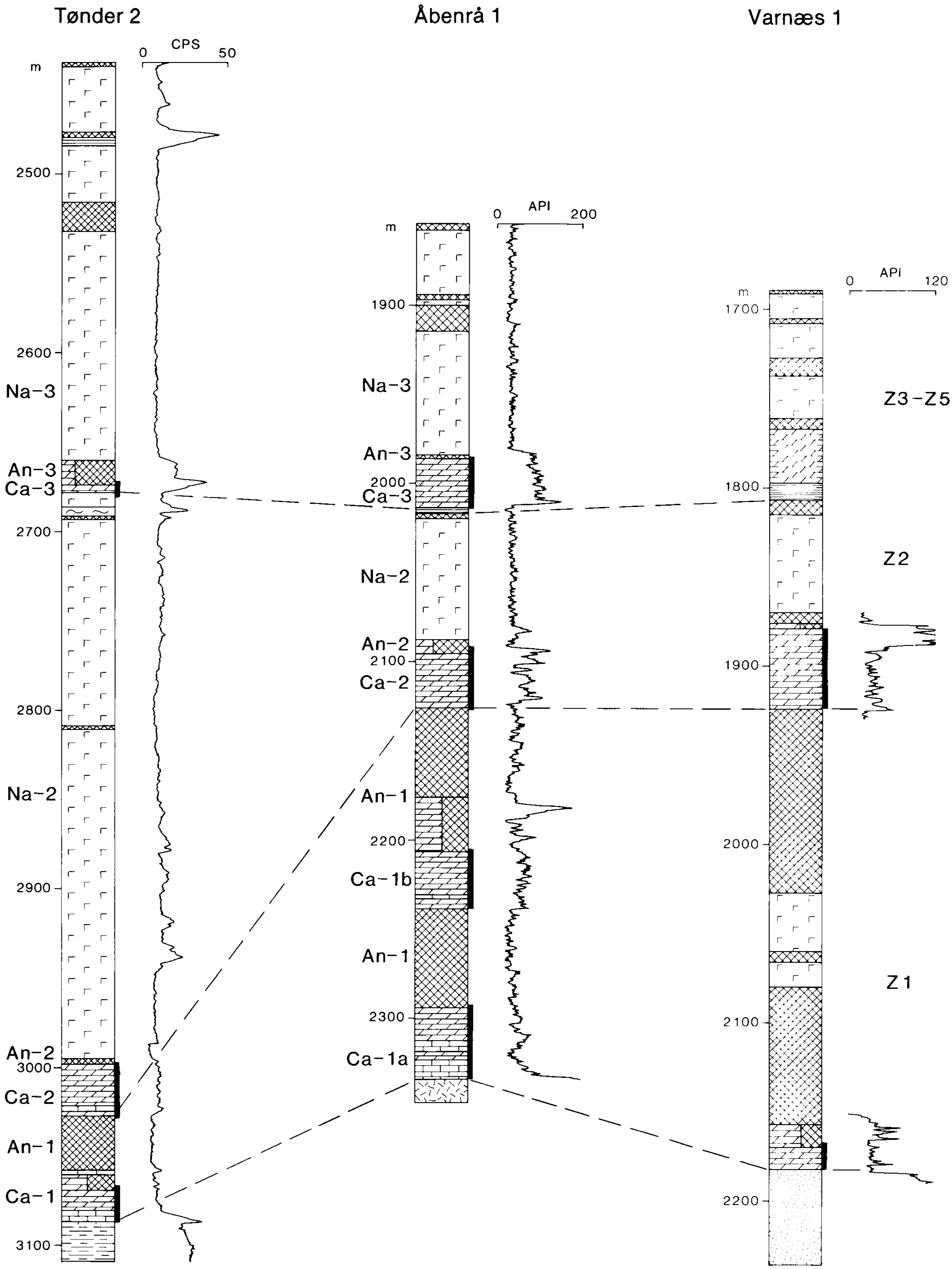


Figure 4. Lithostratigraphic correlation of investigated wells in southern Jylland. Lithology based on core-data and log interpretation. Gamma-ray logs shown for each well. Cored intervals marked by black bars. Legend see fig. 5.



Tønder 2
Åbenrå 1
Varnæs 1
CPS
0
50
API
0
200
API
0
120
m
2500
2600
2700
2800
2900
3000
3100
1900
2000
2100
2200
2300
1700
1800
Na-3
An-3
Ca-3
Na-2
An-2
Ca-2
An-1
Ca-1
Ca-1b
Ca-1a
Z3-Z5
Z2
Z1

Stratigraphy

The Zechstein Group (Michelsen 1986) in southern Jylland is composed of a cyclic repetition of carbonate, anhydrite and salt. The majority of wells available in this study are situated in the marginal areas (fig. 4) therefore comprising thick carbonate and anhydrite units and thin salt intervals. In contrast, the Tønder-2 well situated in the basin is composed mainly of salt with only thin intervals of interbedded carbonate and anhydrite (fig. 4). The cyclic pattern is well developed both in the platform and the basin successions, and facilitates correlation (fig. 4).

Previously, Sorgenfrei & Buch (1964) and Clark & Tallbacka (1980) have proposed lithostratigraphic subdivisions of the Zechstein succession in southern Denmark. Clark & Tallbacka (1980) divided the succession into five units – Z-1 to Z-5 – which could be correlated to similar cycles in the Zechstein of Germany (Richter-Bernburg 1953). This five fold subdivision of the Zechstein succession is widely accepted and will also be used in this study. However, in the Danish sequence, the cycles above Z-3 are difficult to define due to lack of fully developed cycles. Therefore, detailed correlation of Z-4 and Z-5 has not been attempted (fig. 4). As previously pointed out (Clark & Tallbacka 1980) the Danish Z-1 cycle includes two carbonate units, Ca-la and Ca-lb (fig. 4). This deviates slightly from the pattern elsewhere in the German basin (Clark & Tallbacka 1980) and the possible origin of the Ca-lb carbonate unit will be discussed later. Correlation of the Zechstein succession to the standard division of the Permian is problematic. The most widely accepted correlation places the Zechstein in the Tatarian (e.g. Visscher 1972, Ecke 1987).

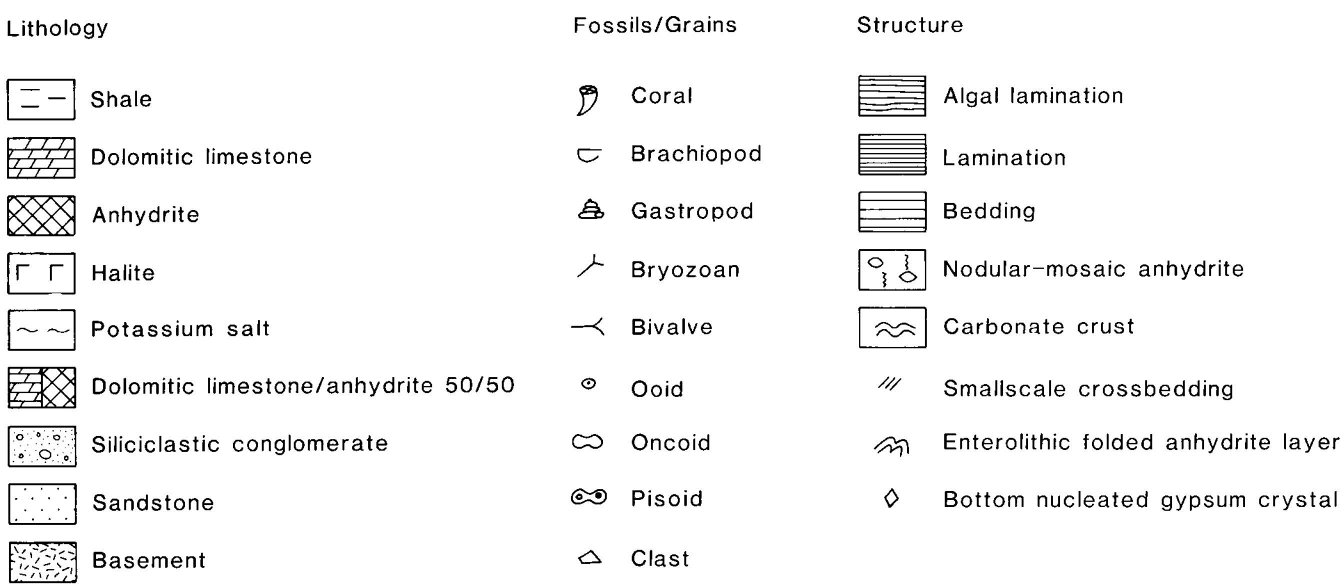


Figure 5. Legend covering figs. 4, 23, 24, 25 and 26.

Sedimentology

The Zechstein deposits of southern Jylland have been penetrated in a number of deep wells. The present description of the lithology and facies is based on cored material from the Arnum-1, Brøns-1, Hønning-1, Løgumkloster-1, Tønder-1, Tønder-2, Varnæs-1 and Åbenrå-1 wells (fig. 4).

Carbonate facies

The Zechstein-1, -2, and -3 carbonate units are subdivided into eight different carbonate facies and two anhydrite facies; siliciclastic rocks form a minor part of the sequence and are only briefly described here. The following descriptions focus on the primary sedimentary features of the rocks using the classification of Dunham (1962) for the carbonates and the classification of Maiklem et al. (1969) for the anhydrite. The complex diagenetic history of the carbonates is discussed elsewhere (Stentoft & Nygaard 1985, 1986, Stemmerik et al. 1987, Stentoft, in press).

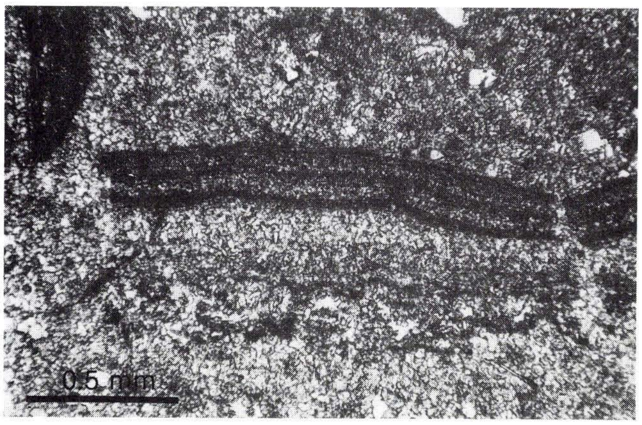


Figure 6. Microphotograph. Dolomite with broken algal crusts. Algal boundstone facies, Ca-la, Åbenrå-1, 2303.00 m.

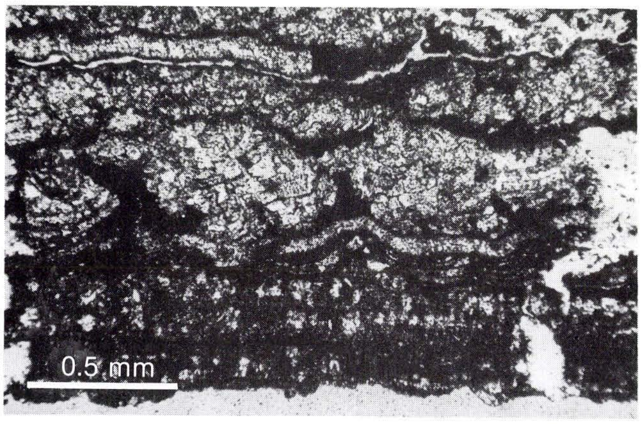


Figure 7. Microphotograph. Dolomite with irregular algal lamination. Algal boundstone facies, Ca-la, Åbenrå-1, 2303.90 m.

Algal boundstone

This facies consists of finely laminated (0.1–1 mm thick) carbonate mudstone. The lamination is undulating and often disturbed (figs. 6, 7). Contorted layers, internal discontinuities, cracks and tepee structures are common. Displacive anhydrite nodules, enterolithically folded anhydrite layers and small anhydrite pseudomorphs after gypsum crystals are often associated with this facies.

In modern carbonate environments algal laminated limestones form in the protected intertidal and subtidal parts of hypersaline lagoons (Shinn 1983). The algal boundstone facies in the Danish Zechstein carbonates is suggested to represent deposition in comparable environments. Sequences composed entirely of undisturbed algal laminated mudstone without displacive anhydrite, probably represent deposition in subtidal settings. Sequences showing contorted layers, tepee structures and various types of displacive anhydrite by comparison to modern equivalents are suggested to represent intertidal and supratidal sedimentation (cf. Warren 1982, Butler, Harris & Kendall 1983, Warren & Kendall 1986).

The algal boundstone facies occurs in all the Zechstein carbonate units.

Mudstone

The mudstone facies is composed of homogeneous lime mudstone occasionally containing a sparse fauna of foraminiferas and bivalves (figs. 8, 9).

The high content of mud suggests deposition in protected areas below wave-base. The scarcity of body fossils suggests a high-stress, inhospitable environment. The absence of lamination is taken as an indication for bioturbation of the sediment thus infering that the bottom conditions were suitable for at least some animals.

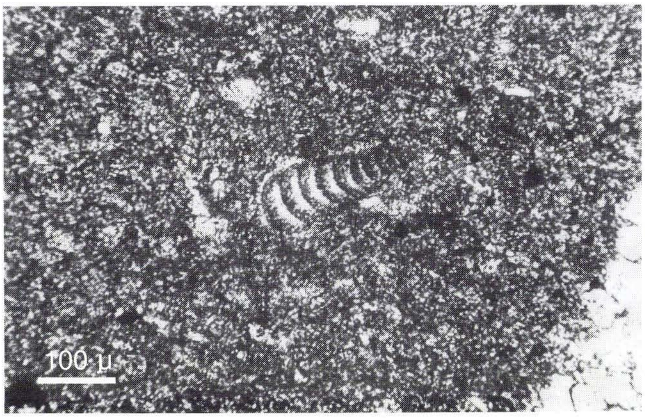


Figure 8. Microphotograph. Uniserial foraminifera in dolomite. Lime mudstone facies, Ca-la, Åbenrå-1, 2331.40 m.

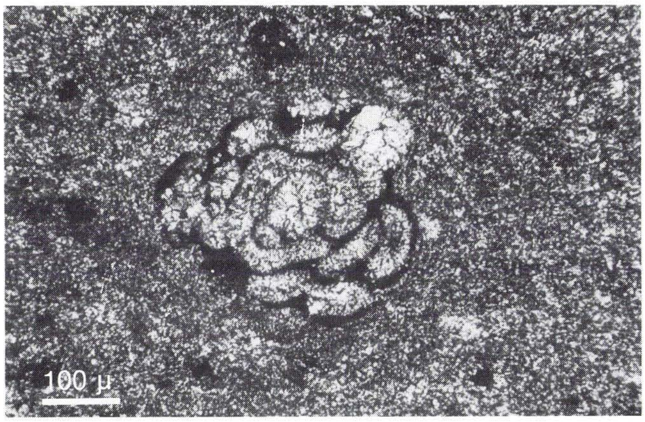


Figure 9. Microphotograph. Glomospirid foraminifera in dolomite. Lime mudstone facies, Ca-la, Åbenrå-1, 2332.00 m.

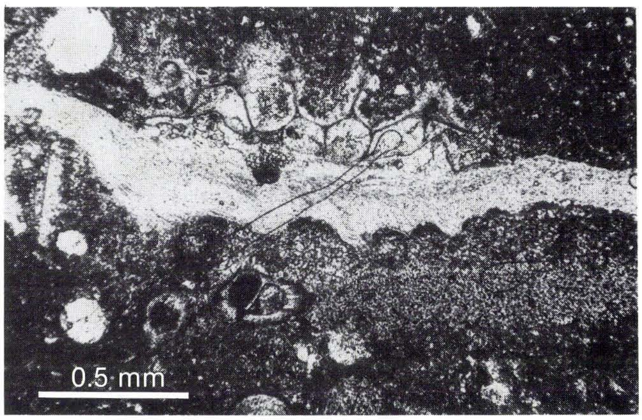


Figure 10. Microphotograph. Punctate brachiopod shell with encrusting bryozoan. Skeletal wackestone facies, Ca-la, Åbenrå-1, 2333, 65 m.

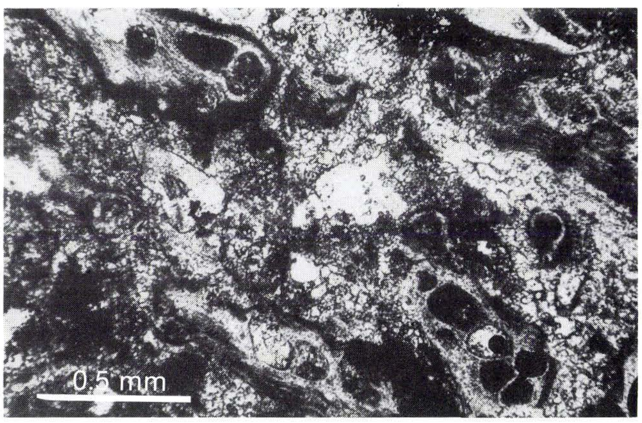


Figure 11. Microphotograph. Fragmented bryozoans. Skeletal wackestone facies, Ca-la, Åbenrå-1, 2333.60 m.

Laminated mudstone

This facies differs from the preceeding by being finely laminated. The lamination is planar and individual laminae are usually less than 0.1 mm thick. The laminated mudstone facies often contains thin layers of homogeneous mudstone. At certain levels, it is disturbed and contorted and kink folded layers alternate with undisturbed layers.

The fine even lamination and the absence of fossils suggests deposition in biologically stressed (?anoxic) environments well below wave base. This facies resembles base-of-slope facies of the Stinkdolomit member (Ca-2) in the Netherlands described by Clark (1980) and is accordingly interpreted as the result of deposition in a comparable setting.

Skeletal wacke- and packstone

This facies consists of biogenic skeletal material and oncoids in a matrix of carbonate mud. The fauna is dominated by fragmented bryozoans and brachiopods and also includes bivalves, corals and foraminiferas (figs. 10, 11). The fossils are worn during their transport into the muddy environment suggesting reworking by waves or currents.

This facies is suggested to represent deposition of material transported from algal-bryozoan mounds to surrounding more muddy environment. Thick accumulations of this facies occur associated with bryozoan mounds. Thin beds (1–3 cm), interbedded with mudstone, represent sediments brought into more distal basinal settings.

Biogene wacke-/packstones only occur in the Ca-la (e.g. Tønder-2 and Åbenrå-1).

Bryozoan bafflestone

Bryozoan bafflestones consist of large, *in situ* colonies of funnel shaped fenestellid bryozoans partly overgrown by early marine cement, algae and carbonate mud (figs. 12, 13, 14, 15). This facies forms 3–5 m thick beds which alternate with beds of biogene wackestone described above (Stentoft & Nygaard 1985).

This facies is suggested to represent part of small bryozoan-algal mounds. The association with algae indicates deposition within the photic zone (<25 m). The

Figure 12. Fenestrate bryozoan forming part of bryozoan mound. Ca-la, Åbenrå-1, 2308.10 m.

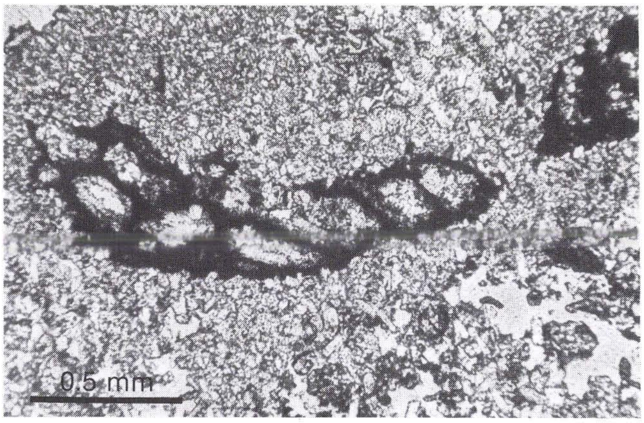


Figure 14. Microphotograph. Dolomite with bryozoan fragment. Bryozoan bafflestone facies, Ca-la, Åbenrå-1, 2303.40 m.

Figure 13. Bryozoan bafflestone facies showing mouldic porosity. Ca-la, Åbenrå-1, 2308.40 m. Coin diameter 15 mm.

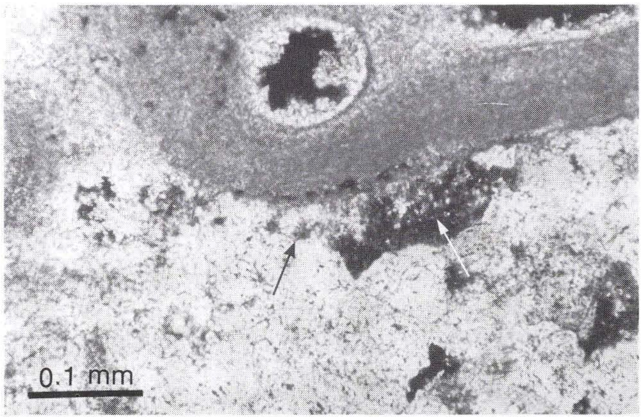


Figure 15. Microphotograph. Ghost of early marine cement on bryozoans. Arrows point to the outer surface of the former marine cement. Ca-la, Åbenrå-1, 2308.00 m.

mounds, like bryozoan mounds elsewhere in the Late Permian (e.g. Hollingworth & Tucker 1987, Hurst, Scholle & Stemmerik 1989) are associated with submarine cementation. However, the cementation is not as extensive as that described by e.g. Hurst et al. (1989), and it is therefore suggested that deposition took place in more quiet conditions probably close to or below normal wave base.

Oolitic grainstone

This facies includes homogeneous, planar bedded and cross-bedded sediments dominated by ooids, 0.2–0.5 mm in diameter (figs. 16, 17, 18). Scattered gastropod fragments occur throughout. The planar bedded units consist of centimetre thick layers of alternating grainsize. Thicker, graded layers also occur. The cross bedded units are dominated by small scale planar structures (fig. 16).

Oolitic grainstones form today in shallow, high energy hypersaline evironments (Bathurst 1976, Halley, Harris & Hine 1983). A comparable environment of deposition is suggested for the Zechstein oolitic grainstones. They are often associated with thin horizons of pisolitic packstone suggesting regular exposure and subjection to freshwater vadose diagenesis.

Oncoid packstone/grainstone

This facies consists of both homogeneous and thin-bedded layers of packstones and grainstones dominated by oncoids, 1–10 mm in size (fig. 19). Scattered fragments of fossils occur throughout.

Oncoids form in hypersaline, moderately agitated environments, thus representing a higher energy equivalent of the algal laminated limestones. This facies occurs only in the Ca-2 of the Arnum-1 well.

Pisolitic packstone/grainstone

This facies consists of a variety of packstones that are all characterised by their content of pisolites, anhydrite filled vugs and laminated carbonate crusts (figs. 20, 21).

The primary sedimentary facies include skeletal packstone, oolitic grainstone (fig. 21) and intraclast conglomerates. Secondary features are pisolites, 2–20

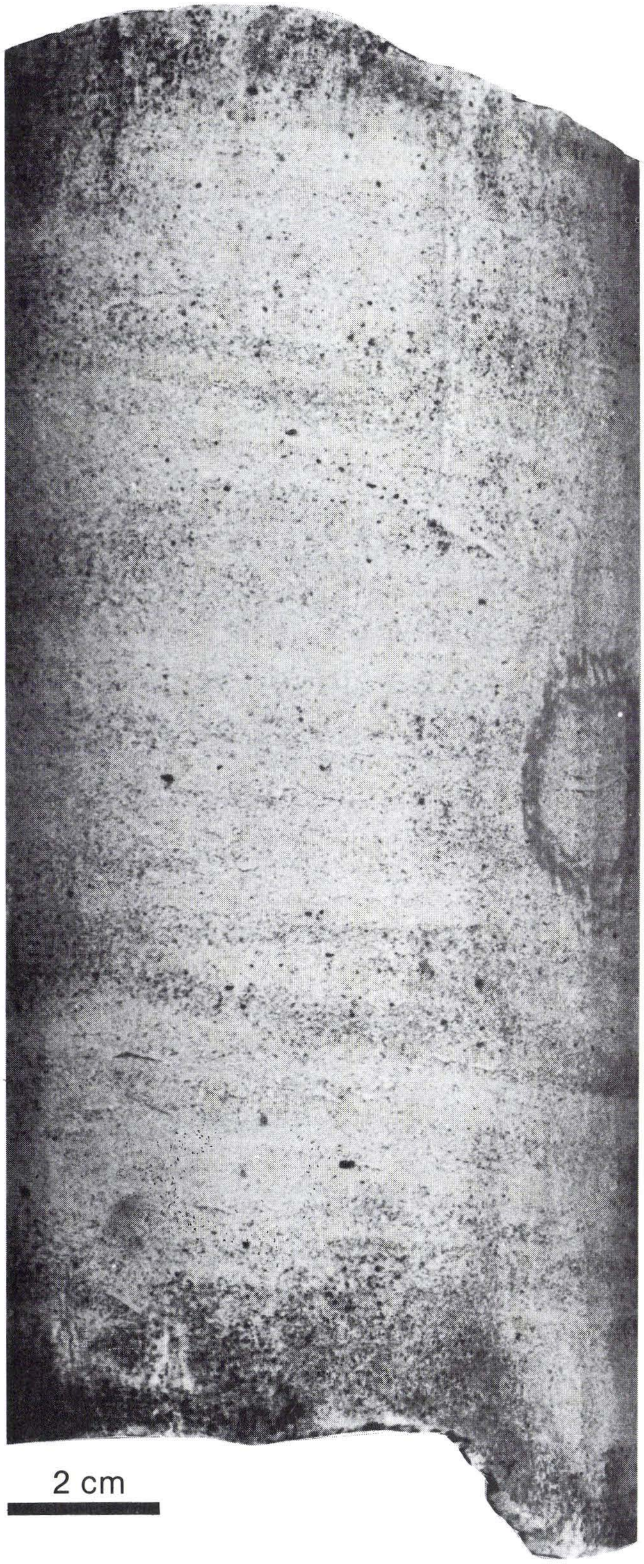


Figure 16. Cross-bedded oolitic grainstone. Note the intragranular porosity. Ca-2, Varnæs-1.

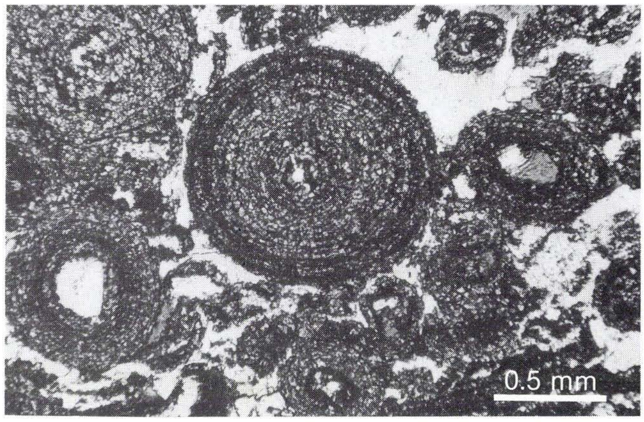


Figure 17. Microphotograph. Ooidal dolostone showing some mouldic porosity. Most of the pore space is filled with anhydrite (light). Løgumkloster-1, Ca-2, 2435.85 m.

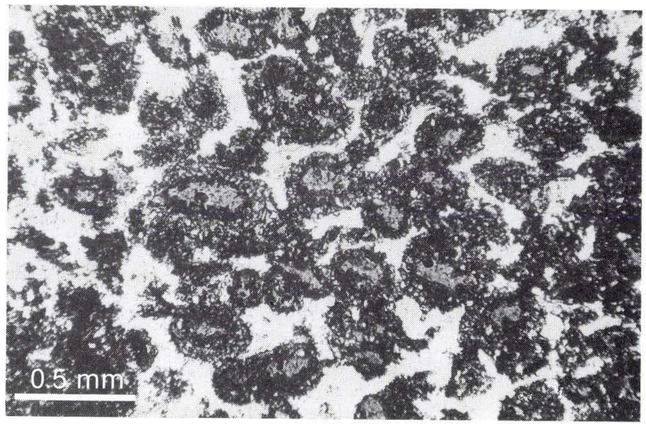


Figure 18. Microphotograph. Ooidal dolostone with mouldic porosity in the internal parts (darkgrey). Anhydrite cement (light) is seen in the interooidal spaces. Løgumkloster-1, Ca-2, 2431.36 m.

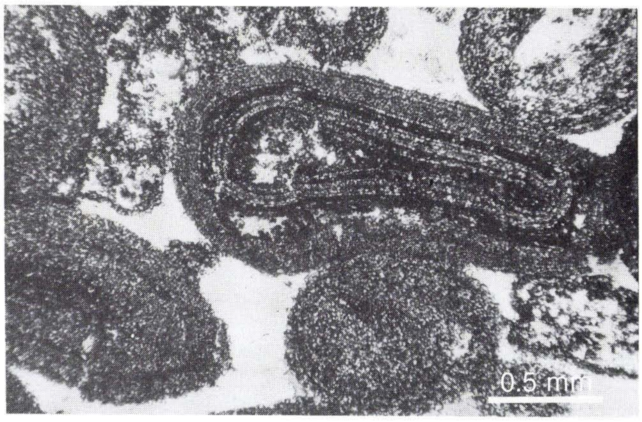


Figure 19. Microphotograph. Dolomite oncoid with very regular lamination and remnants of dark organic matter. Løgumkloster-1, Ca-2, 2441.40 m.

mm in size, wavy laminated carbonate crusts and secondary porosity. This porosity is almost completely filled by late diagenetic anhydrite.

The sediment was originally deposited in a variety of shallow marine moderate to high energy environments (cf. interpretation of the facies mentioned above). Syndepositional exposure subjected the sediments to diagenesis in the zone of meteoric water, resulting in the formation of pisolites and carbonate crusts as well as extensive dissolution. Comparable rocks elsewhere in the Zechstein Basin have been interpreted in a similar fashion (e.g. Clark 1980, Peryt 1985, 1986a). This facies occurs in Ca-la and Ca-2.

Figure 20. Pisolitic grainstone facies. Note the anhydrite filled vugs (arrows). Ca-2, Varnæs-1.

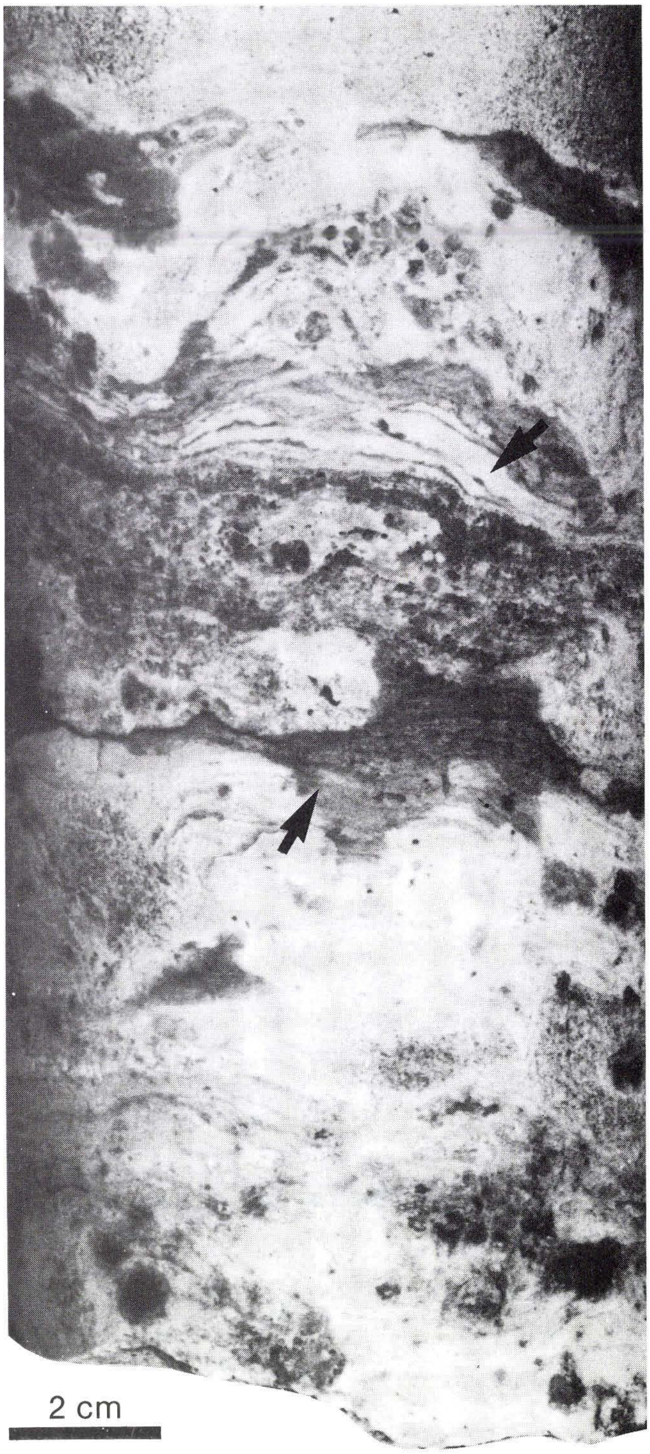


Figure 21. Pisolitic grainstone overlain by oolitic grainstone. Note the well-developed carbonate crusts in the pisolitic grainstone (arrows). Ca-2, Varnæs-1.

Nodular and nodular-mosaic anhydrite

This facies is characterised by displacive anhydrite nodules forming nodular and nodular mosaic anhydrite (fig. 22). The nodular units consist of isolated anhydrite nodules within algal laminated carbonates. In the nodular-mosaic anhydrite the density of nodules is so great that the original carbonate fabric is completely obscured.

Anhydrite nodules may form both subaqueously and subaerially (e.g. Dean, Davies & Anderson 1975, Butler et al. 1982). Thin sequences of cyclically deposited algal boundstone, algal laminated carbonate with anhydrite nodules, and nodular-mosaic anhydrite are interpreted as shallowing upwards cycles formed in

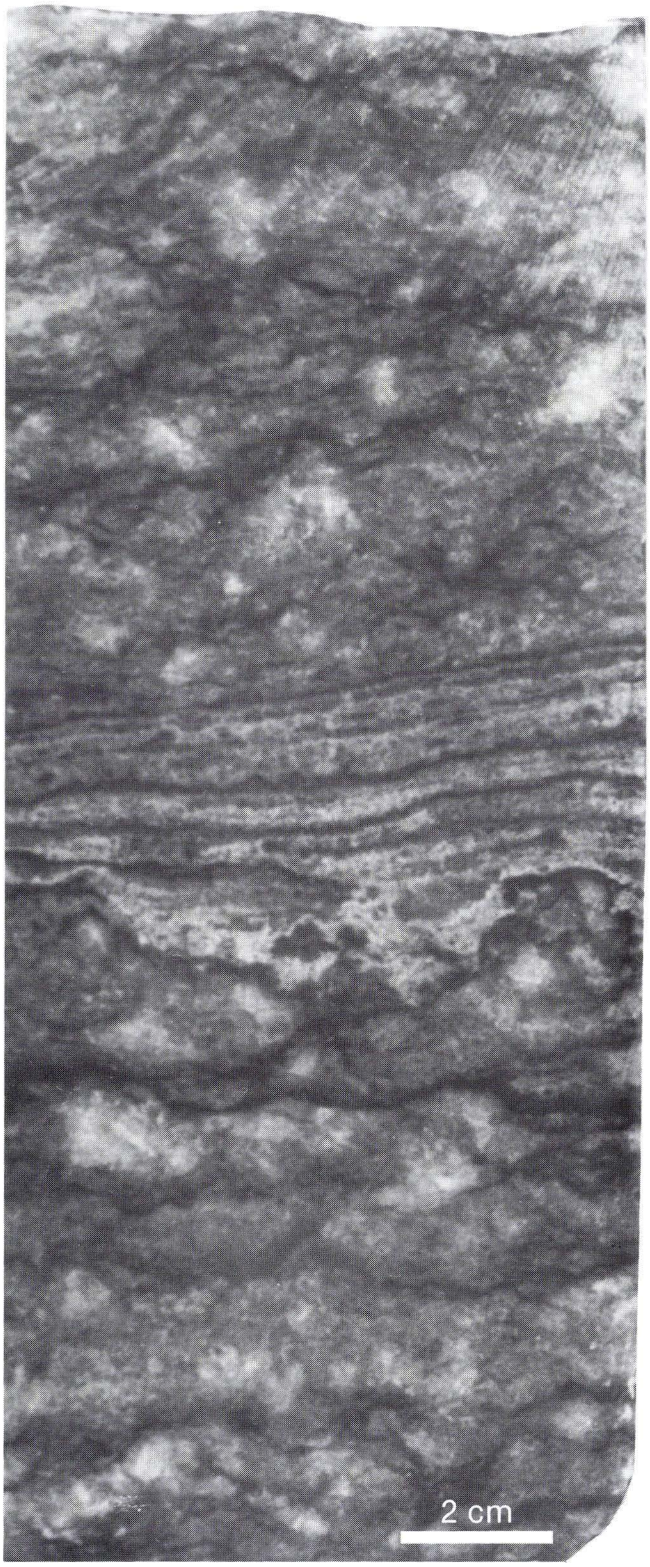


Figure 22. Nodular-mosaic anhydrite with thin algal laminated interval. Z-2, Brøns-1.

sabkha-like environments and therefore indicate subaerial formation of these anhydrite deposits.

In contrast, thick uniform sequences of nodular-mosaic anhydrite probably result from subaqueous growth of anhydrite.

Laminated anhydrite

The laminated anhydrite facies consists of interlaminated anhydrite and carbonate. Two types of lamination occur. Most commonly the lamination is undulating, individual laminae being 1 mm to a few cm thick. The outline of former bottom nucleated gypsum crystals is preserved in the thicker anhydrite laminae. The second type, in contrast, consists of planar laminated sediments with individual laminae in the thickness of less than 0.1 mm.

The first type of laminated gypsum resembles modern deposits described by Kushnir (1981) and Warren (1982) from shallow gypsum ponds. Accordingly, it is suggested to represent shallow water gypsum deposition. The second planar laminated type resembles deep water anhydrite described from elsewhere in the basin (e.g. Richter-Bernburg 1985). A deep water origin is further supported by the close association with the laminated mudstone facies.

Siliciclastic rocks.

Three different types of siliciclastic sediments occur within the cored part of Zechstein succession of southern Jylland. They are of minor importance and are therefore only treated briefly.

a) Black laminated shale equivalent to the Kupferschiefer in Germany and the Marl Slate in England occurs in the basal part of the Ca-la of the Tønder-2 well. It consist of finely laminated (<1 mm) black shale with a moderate content of organic material. These shales are deposited under anoxic conditions in the deeper part of basin.
b) Poorly sorted medium to coarse grained sandstone occasionally with a poorly developed lamination occurs associated with lagoonal limestones in the upper part of Ca-2 in the Arnum-1 well. Isolated displacive anhydrite nodules occur frequently in this facies suggesting deposition in intertidal to supratidal environments. The sandstone probably represents ephemeral stream deposits into shallow lagoons and windblown sand on the surrounding sabkhas.
c) Matrix supported, often normally graded conglomerates occur frequently in the basal part of the sequence. The clasts are mainly erosional products of the underlying basement but rarely include carbonate intraclasts. The matrix consists of poorly sorted sand. The restriction of the conglomerates to the marginal part of the basin suggests deposition from ephemeral streams running off the Ringkøbing-Fyn High.

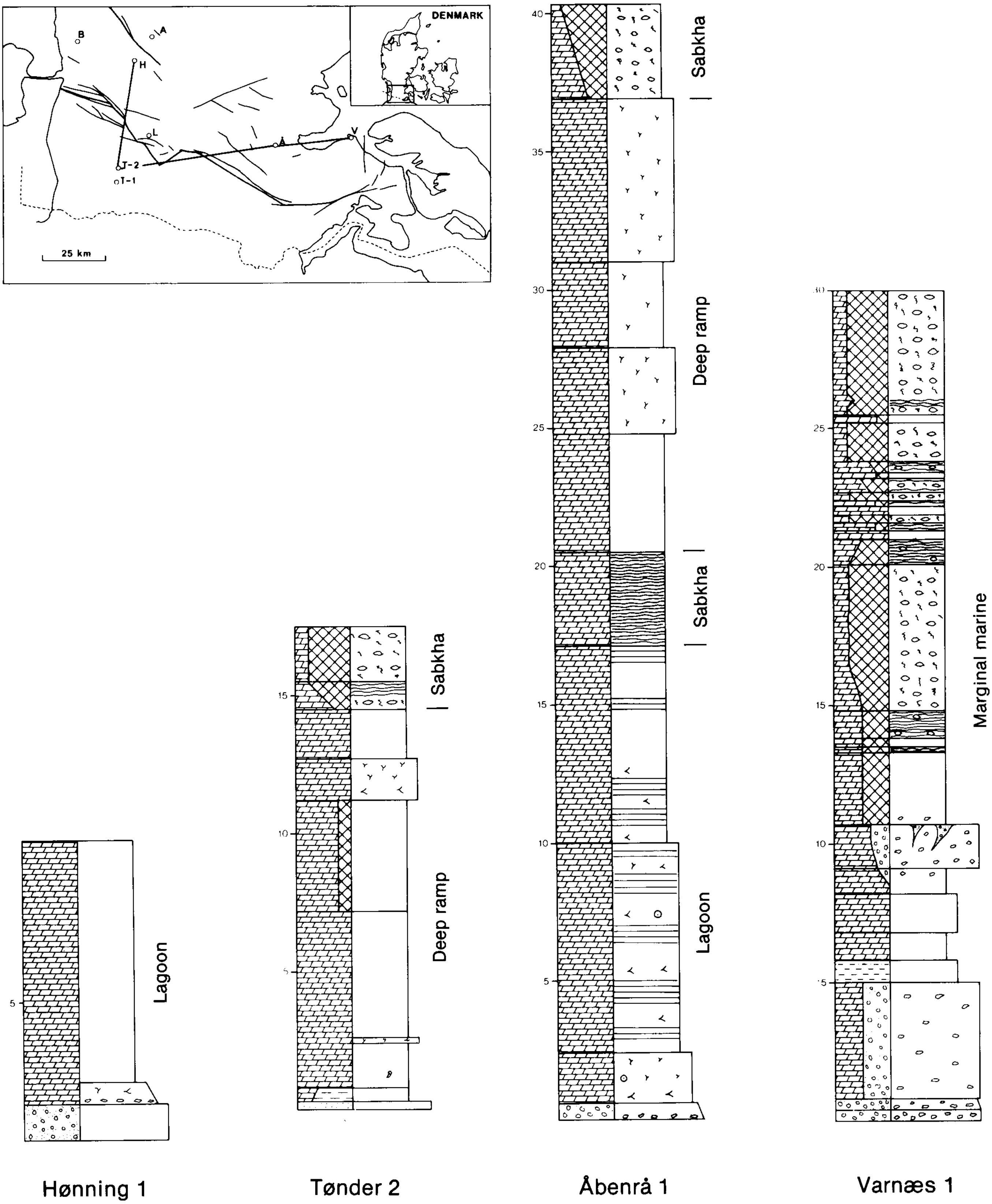


Figure 23. Sedimentology of the cored intervals of Ca-1a. Legend see fig. 5.

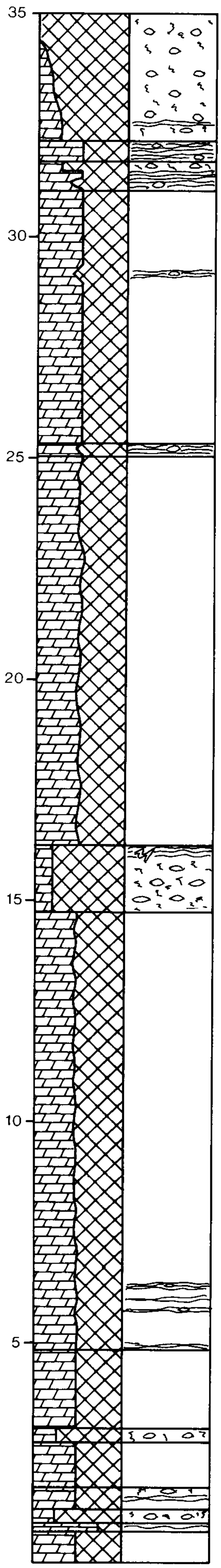


Figure 24. Sedimentology of the cored interval of Ca-lb in Åbenrå-1. Legend see fig. 5.
←

Sedimentary environments

Based on the association of facies and their spatial distribution, seven broadly defined sedimentary environments have been identified within the Ca-la to Ca-3 carbonates of southern Jylland (figs. 23, 24, 25, 26). Open marine conditions occured only during deposition of the Ca-la carbonate. The following units, Ca-lb to Ca-3, only contain restricted faunas of highly tolerant animals such as bivalves and gastropods suggesting deposition in environments with increased salinity. Thus, an overall evolutionary trend towards more saline conditions can be inferred.

Marginal marine (sabkha)

Thick, 5–15 m sequences of algal laminated limestone with abundant interbeds of nodular and nodular-mosaic anhydrite and rare beds of lime mudstone are suggested to represent deposition in marginal marine sabkha-like environments. From studies of modern arid shorelinies (e.g. Butler et al. 1982) such environments are known to form in protected intertidal to supratidal zones.

Lagoon

Lagoonal deposits include 7–30 m thick successions of oncoid packstones and grainstones with subordinate intervals of pisolitic packstones, algal boundstones and siliciclastic conglomerates. The dominance of oncoids indicates biologically stressed conditions in these lagoons. Gastropods and bivalves are common at certain levels, however, suggesting periodic improvement in the environmental conditions.

The dominance of oncoids suggests deposition in slightly agitated environments within the photic zone, most likely in less than 10 m of water. The lagoons regularly became exposed as shown by the occurence of pisolitic packstones. The exposed areas were probably small islands that had locally accreted above sea level. Thus, different parts of the lagoon were probably exposed at different times rather than contemporaneous exposure of the entire lagoon due to a drop in sea level (cf. model by Pratt & James 1986). Comparable features are described elsewhere in the basin (e.g. Clark 1980, Peryt 1986a). However, the lagoonal deposits described here differ from the sequences described by Clark (1980) and Peryt (1986a) in having a significantly less diverse fauna.

Oolite shoal

The oolitic grainstone facies is commonly found as 5–30 m thick uniform accumulations associated only with thin layers of pisolitic grainstone (fig. 25). The thickness of these deposits suggest that they represent oolite shoals. This is compatible with their common position along the margin of the platform as it is defined from seismic data. Comparable modern shoals are well known for example along the platform margins of the Bahama Banks (e.g. Bathurst 1976, Halley et al. 1983), and as a high-energy belt along the hypersaline shores of the Persian Gulf.

The thick uniform sequences of oolitic grainstone are usually associated with intervals composed of interbedded layers of oolitic grainstone and algal boundstone. These intervals were deposited in protected back shoal environments. The algal boundstone thus represents the normal fair weather deposits behind the shoal whereas the interbedded oolitic grainstones represent material washed over the shoal during storms. The frequent occurence of pisolitic grainstone indicates that the shoals commonly accreted to sea-level and occasionally became subaerially exposed and subjected to fresh water diagenesis. Similar processes and fabrics are well described from both modern equivalents and the Zechstein oolite shoals elsewhere in the basin (Clark 1980, Peryt 1985, 1986a). However, beachrock fragments as described by Clark (1980) and Peryt (1986a) have not been identified in the Danish Zechstein.

Deep ramp

This broad environmental category includes the bryozoan mounds and their associated deposits as well as the mudstone facies found in the Ca-la unit. It differs from the previous described environments by being normal marine or only slightly salinity stressed. As previously stated the bryozoan mounds appear to represent deposition close to normal wave base. They are associated with algae that indicate a maximum depth of 25–50 m. The intense bioturbation of the mudstone indicates oxic bottom conditions in contrast to the basinal mudstone environment developed in Ca-2. Analogous sequences in the Carboniferous of Wales is interpreted to represent outer ramp environment (Wright 1986).

Base of Slope

The laminated mudstone facies showing syndepositional slump features resembles facies sequences described by Clark (1980) from a base of slope environment. Thick sequences of laminated mudstone at the base and top of the Ca-2 unit in the Tønder-2 well may represent the basin floor.

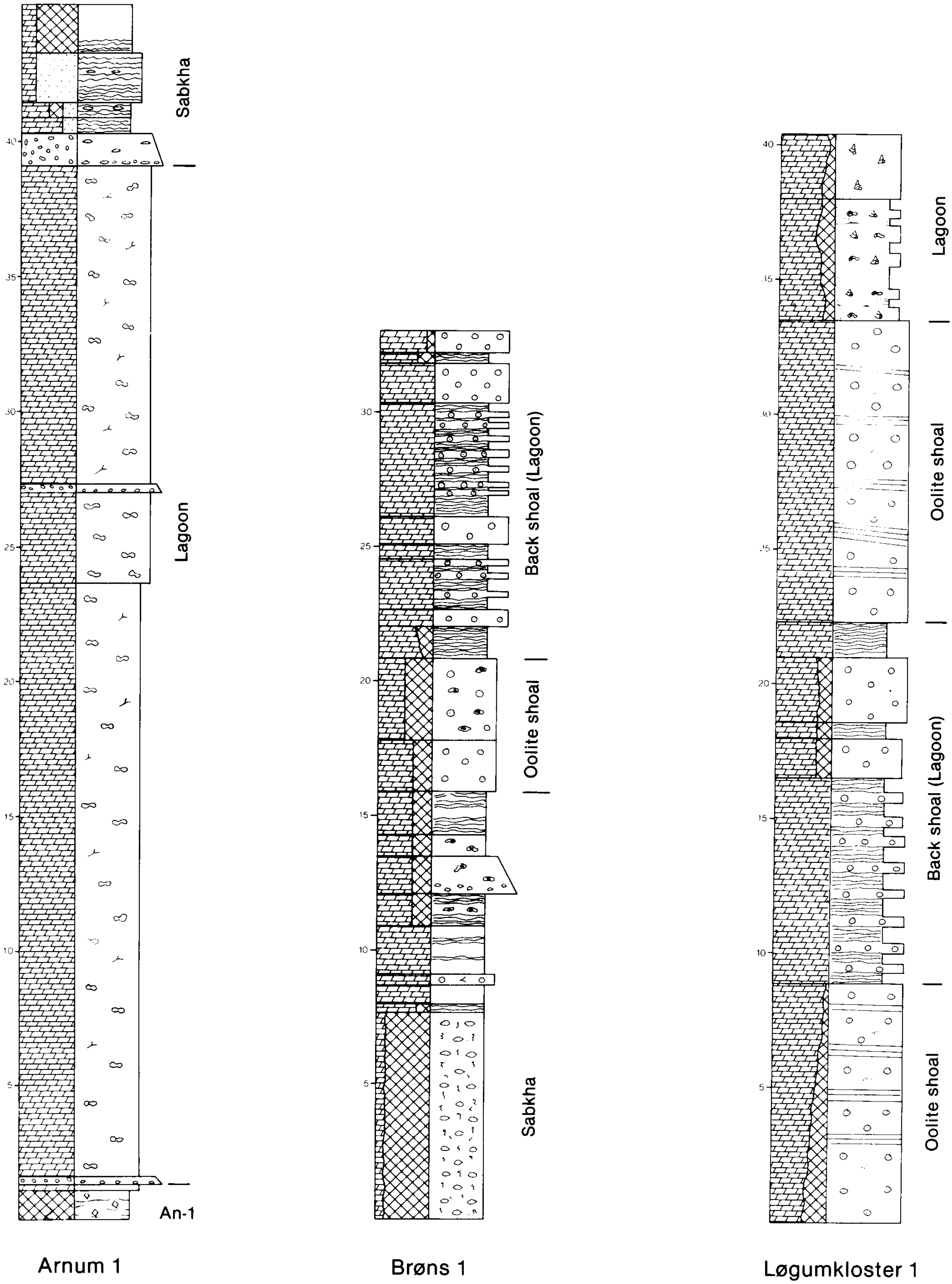


Figure 25. Sedimentology of the cored invervals in Ca-2. Legend see fig. 5.

DENMARK
25 km
B
A
H
L
T-2
T-1
Å
V
Sabkha
Lagoon
Oolite shoal
Sabkha
An-1
Base of slope
An-1
Lagoon
Oolite shoal
Sabkha
Tønder 2
Åbenrå 1
Varnæs 1

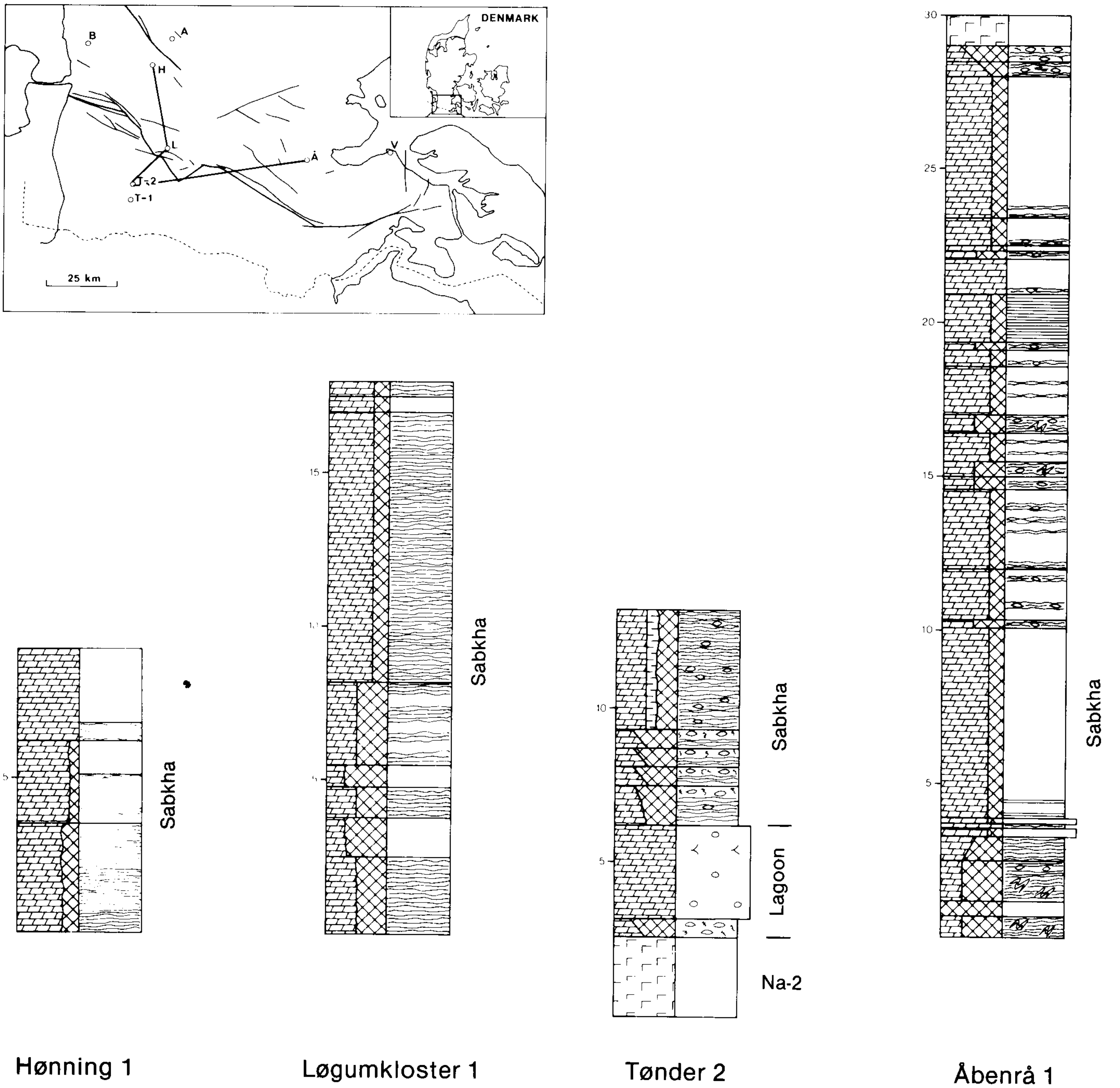


Figure 26. Sedimentology of the cored intervals in Ca-3. Legend see fig. 5.

Basin evolution

Basement

The Zechstein deposits overlie a variety of rocks including Precambrian crystalline basement, Lower Palaeozoic metamorphic rocks (Caledonian) and Lower Permian Rotliegendes sediments (figs. 3, 4). The Precambrian crystalline basement is found on the Ringkøbing-Fyn High (e.g. Arnum-1). Metamorphic Lower Palaeozoic basement is encountered in the platform area south of the Ringkøbing-Fyn High (e.g. Brøns-1 and Løgumkloster-1). In this area, Permian Rotliegendes also occurs in small fault-controlled basins (fig. 3). This configuration attests to a very deep erosion level prior to the deposition of the Zechstein sediments. Faulting created a block pattern that was most pronounced in the crystalline terrain of the Ringkøbing-Fyn High e.g. the Arnum Block, but was also present in the metamorphic Caledonian basement (fig. 3). Deposition of the siliciclastic Rotliegendes was not sufficent to fully level out the relief. The Zechstein basin therefore formed an enormous depression estimated to be as deep as 200 m below sea-level (Smith 1980). In southern Jylland and probably elsewhere in the basin, the relief was maintained by continuous subsidence, probably associated with minor faulting.

Depositional model for the Ca-la carbonate ramp

Following initial flooding of the basin, carbonate sedimentation was established throughout most of the investigated area, except on basement highs and in the deepest part of the basin. Siliciclastic deposits are thus very sparse. Thin sequences (<3 m) of conglomerate occur in the wells closest to the Ringkøbing-Fyn High. On the Arnum block a thick conglomerate sequence overlies the basal unconformity. However, this may correlate with a higher level within the Z-1 anhydrite. The characteristic basal clastic unit equivalent to the Kupferschiefer well known from the German and Polish sections is restricted to the deeper part of the basin (Tønder-2) where it is less than 1 m thick.

The Ca-la unit can be subdivided into two subunits. This subdivision was documented for the Åbenrå-1 well by Stentoft & Nygaard (1985); at present this subdivision is not firmly established in the Ca-la sections in the Hønning-1, Tønder-2 and Varnæs-1 wells (fig. 23). Each sub-unit is composed of a shallowing-upward sequence that probably reflects a fluctuation of sea-level. A comparable subdivision of the basal carbonate Ca-la unit has been established elsewhere in the basin (Smith 1980, Peryt 1978, 1986b, Paul 1986a, b, 1987 and Pöhlig 1986), and is generally believed to reflect eustatic (regional) fluctuations in sea-level (e.g. Peryt 1986, Pöhlig 1986).

The depositional environments interpreted from core-descriptions are best accomodated on a ramp, deepening southwards (fig. 27). The Varnæs-1 well is dominated by inter- to supratidal facies. The Hønning-1 and Åbenrå-1 wells reflect deposition close to normal wavebase. The Ca-la unit in the Tønder-2 well is thin in comparision to more northern wells and indicates a deeper water setting. Although no core-material exists for the Ca-la unit in the Løgumkloster-1 well, log data suggests that the interval is remarkably thin, only 2 m compared to over 20 m in the Tønder-2 well. A possible explanation for this is local sediment starvation at Løgumkloster-1 because of an elevated position on an upthrown fault-block (see fig. 3). During deposition of Ca-la there is no indication of a pronounced platform margin.

Deposition of the Ca-la unit was ultimately terminated by a significant sea level fall, exposing the deepest known parts of the ramp in the Tønder-2 well (fig. 23). The sea level drop was accompanied by sedimentation of a thin sabkha sequence of mixed carbonate/anhydrite as the supratidal zone downstepped the ramp. Such sea level drop at this stratigraphic level has also been suggested by Pöhlig (1986) to explain a facies change from carbonates up into anhydrite deposits in some German sequences.

Depositional model for the An-1 platform construction

The An-1 sequence varies in thickness from 25 to 250 m; locally it includes thick carbonate intervals, the thickest of which is termed the Ca-lb carbonate unit (Clark & Tallbacka 1980, Stemmerik et al. 1987). Intervals of halite also occur, the most prominent recorded in the Varnæs-1 well (10 & 30 meter thick; fig. 4). As outlined here, the depositional pattern of the Z-1 cycle is complex and involves the interplay of several factors such as eustasy, the position of the chemocline and the depositional rate of sulphate evaporites.

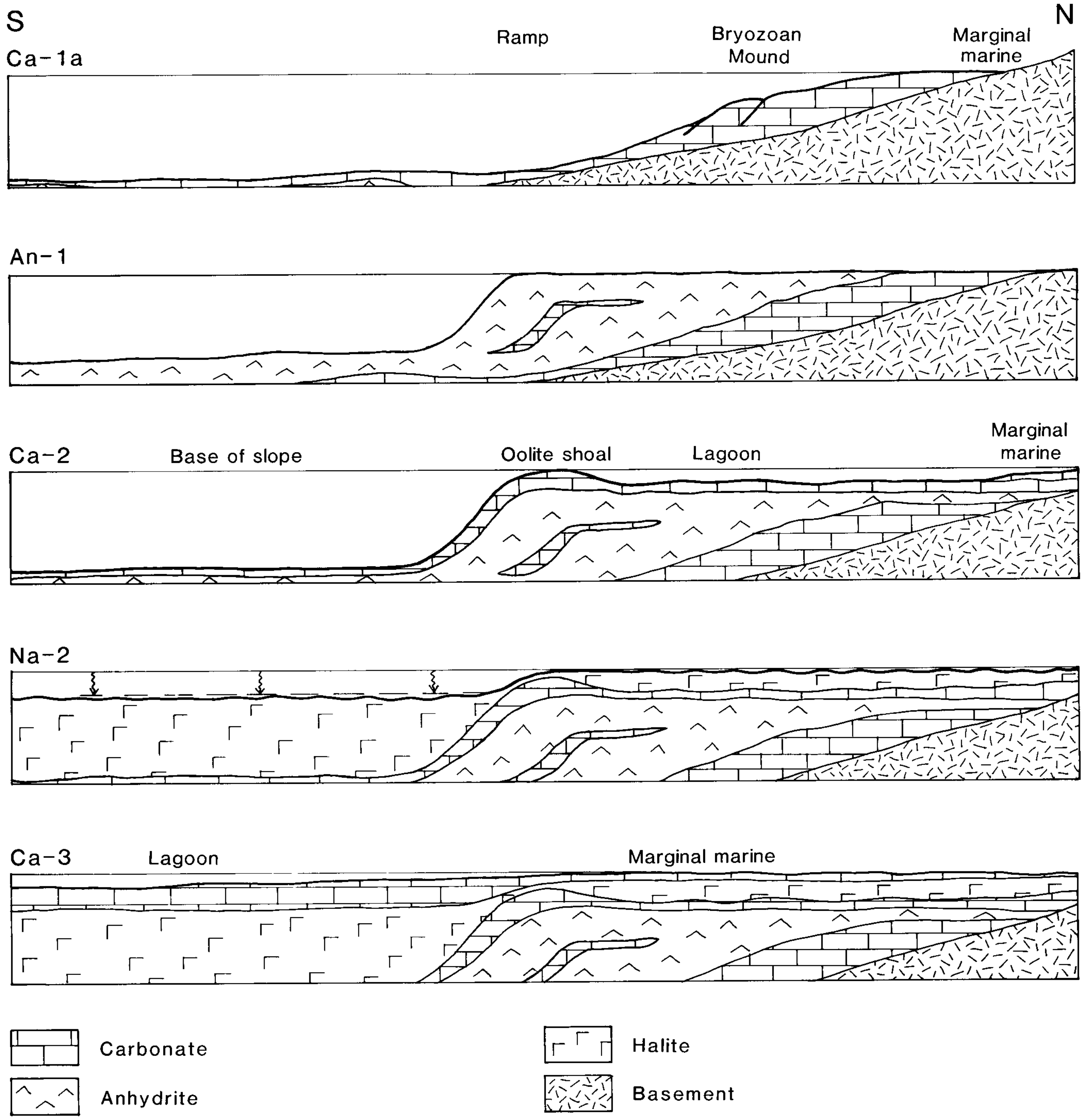


Figure 27. Schematic N-S profile showing sequence of platform evolution and demise during deposition of the Zechstein carbonates.

Ca-1a: Initial ramp deposition of Ca-1a with possible bryozoan mounds.

An-1: Platform construction by progradation of anhydrite deposits. During this progradation, intervals with carbonate deposition occured (Ca-1b).

Ca-2: Deposition of Ca-2. The platform morphology created during An-1 times was inherited by the depositional pattern for the Ca-2.

Na-2: Platform demise by filling of the basin with halite during Z-2. A possible sea-level drop is causing halite saturation over the whole basin.

Ca-3: Deposition of Ca-3 as shallow-water carbonates overlying also former basinal deposits as the topography is levelled out by the thick Na-2 halite.

After the regression that terminated deposition of Ca-la carbonates, renewed flooding reestablished a sea level close to the previous depositional surface. The waterbody was apparently saturated with respect to sulphate, and the carbonate/sulphate chemocline was close to the sea level. Thus, the rapid sea level rise only left a thin supratidal anhydrite unit to record the transgression onto the carbonate ramp. The subsequent high sea level stand allowed progradation of supratidal anhydrite sequences.

Progradation extended from all positive areas. If implemented on an original complex island/lagoon topography, such progradation would have resulted in local isolated lagoonal areas where halite deposition could occur. Such semi-stationary salt-pans were probably responsible for the salt intercalations in the An-1 anhydrite, e.g. in the Varnæs-1 well.

Progradation of the shallow-water anhydrite deposits gradually changed the morphology of the shelf from a ramp to a platform, which possessed a steep margin separating shallow-water areas from the basinal environments. The front of this margin was apparently the site of occasional carbonate deposition (fig. 27). This could have resulted from a temporarily lowered $CaCO_3/CaSO_4$ chemocline when improved circulation imposed carbonate saturation on this exposed location. Many thin carbonate intercalations are found in the An-1 sequence, and this is also a common feature of the German An-1 sequence (Pöhlig 1986). The most well developed carbonate units attain thicknesses of more than 50 meters. In the Danish sections one such carbonate unit has been named the Ca-lb (Clark & Tallbacka 1980, Stemmerik et al. 1987), although it is not a laterally persistent unit and is not found in all sections. The recognition of the Ca-lb carbonates as a discrete stratigraphic unit is probably partly an accident of history as one of the earliest wells drilled in the southern Jylland through the Zechstein was the Åbenrå-1 well where a thick Ca-lb unit was developed (figs. 4, 24). Later drilling has shown the unit to be impersistent through the region, but the integrity of the unit is retained here and in recent publications (Stemmerik et al. 1987). It is suggested here, however, that the status of unit Ca-lb should be considered with care in any future formal stratigraphic studies.

Given the pattern of anhydrite platform progradation during Z-1, a thick Ca-lb carbonate unit may have formed at the platform margin during periods of vertical aggradation of the margin, rather than progradation (fig. 27). Aggradation would result from a relative sea level rise and could be accompanied by enhanced circulation, thus suppressing the chemocline. Carbonate deposition would be restricted to a belt along the anhydrite platform margin, whilst anhydrite deposition continued on the platform itself and also in deeper water due to sulphate saturation below the chemocline. The two examples of distinct carbonate sequences (Ca-lb), in the wells Hønning-1 and Åbenrå-1 (fig. 24) probably represent this temporary carbonate belt, although diachrony between the carbonate intervals cannot be ruled out.

The interval with dolomite stringers in the An-1 unit in the Løgumkloster-1 well is suggested to be a minor expression of the same trend, probably developed at a later stage when the platform margin had moved farther offshore.

The An-1 anhydrites are mostly developed as nodular anhydrite in the wells drilled on the platform. The upper part of An-1 in the Tønder-2 well is composed of a condensed sequence of laminated anhydrite indicating deeper water conditions in this southern area.

A net rise in the sea level during the An-1 deposition is indicated by the thin anhydrite sequence transgressing the Arnum Block, given that the overlying carbonate unit can be correlated with the Ca-2 carbonate unit advocated by Clark & Tallbacka (1980) and Stemmerik et al. (1986, 1987).

Depositional model for the Ca-2 carbonate platform

The change from anhydrite to carbonate saturation of the watermass resulted from destruction or lowering of the chemocline, associated with apparently only a minor rise in sea level. A similar model has been suggested by e.g. Sønderholm (1987) for the Zechstein 1–2 transition zone in northern Denmark. The Ca-2 is the most widespread carbonate unit and is even interpreted to cover the Arnum Block (Stemmerik et al. 1986, 1987). The platform morphology inherited from the Z-1 depositional phase gave rise to significant carbonate facies differentiation, in particular producing a clear distinction between platform and basinal deposits (fig. 27).

In southern Denmark a minimum depth of the basin at the beginning of Z-2 time can be roughly estimated from the thickness of the Na-2 sequence. The rate of halite sedimentation is assumed to be relatively high and the influence of contemporaneous subsidence may therefore be neglected. Deposition of the Na-2 halites levelled out the pre-existing basin-platform topography almost completely (fig. 27). Thus the difference between the thickness of Na-2 in the basin and on the platform can be taken as an indication of the original depth of the basin when Na-2 deposition was initiated. This estimate gives a depth range of 400 to 500 m.

A similar argument has been put forward by Sannemann et al. (1978) for the Z-2 halite in NW Germany; they suggest basinal depths in this region of at least 400 meters at the beginning of Z-2 times.

The depositional model for the Ca-2 unit has previously been outlined by Stemmerik et al. (1986, 1987). On the platform itself, the presence of a high energy barrier at the margin and resultant restricted circulation behind, created a complex pattern of depositional environments.

The lateral distribution of environments on the western part of the platform (fig. 25) fits well into a well-known model of deposition on a hypersaline carbonate platform (e.g. Kendall & Skipwith 1969, Bathurst 1976, Clark 1980, Wilson 1975). Oolite shoals formed in shallow high energy environments along the platform margins. On the leeward side of the shoals, algal laminated limestone was deposited in protected subtidal environments, which periodically were supplied with oolitic sediment that spilled over the shoals during storms. Landward from the shoals, oolitic material became less important, and wide, protected lagoons prevailed, dominated by shallow subtidal-supratidal sedimentation (fig. 25). Moderately agitated open lagoons apparently developed in localised deeper areas, probably with more frequent connection with the open marine environment outside the oolite barrier.

In the Hønning-1 well, the unit equivalent to Ca-2 is inferred from wireline logs to consist of interbedded anhydrite, clastics and carbonates. It is suggested that these deposits represent a supratidal anhydrite wedge of (?)sabkha origin that formed along the margin of the Arnum Block. Anhydrite deposition was periodically interrrupted by deposition of conglomerates which occasionally can be traced into the Arnum-1 well (fig. 25).

The distribution of environments on the eastern part of the platform seems more simple as only oolite shoals occured (fig. 25). Back-shoal environments have not been recognised. This may reflect a shallow more agitated environment of deposition with continuous migration of the oolite shoals. This is compatible with the development of several horizons of pisolitic packstones that can be correlated from the Åbenrå-1 to the Varnæs-1 well over a distance of 30 km, suggesting exposure of huge areas of the eastern platform on several occasions during deposition of the Ca-2 carbonates.

The basinal deposits constitute a rather homogeneous sequence compared to the complex development of the platform area. The Ca-2 unit is composed of thick sequences of laminated lime mudstones occasionally interrupted by 5–20 cm thick intervals of homogeneous lime mudstone in the Tønder-1 and -2 wells. Contortion structures and kink bands comparable to those described by Clark (1980) from basinal Ca-2 facies in the Netherlands occur only rarely.

By comparison to the Ca-2 unit in the Netherlands (Clark 1980) the Tønder-1 and Tønder-2 wells appear to represent a base-of-slope setting within the basin.

Z-2 platform demise

Overlying the Ca-2 in the basin is a thick sequence of halite (ca. 500 m original thickness in Tønder-1 and -2) (fig. 27). The halite extends onto the platform setting in most wells and is commonly associated with anhydrite intervals.

This indicates a drastic rise of the $CaSO_4/NaCl$ chemocline inducing NaCl saturation over the whole basin. Deposition of thick halites in the basin resulted in a general levelling of the former relief and ultimately lead to the demise of the platform.

Depositional model for the Ca-3 carbonate

Deposition of Z-3 carbonates was widespread in southern Jylland (fig. 4). In contrast to the earlier carbonate units (Ca-1 and Ca-2), the Ca-3 carbonate unit exhibits marked thinning from 30–50 m on the platform in northern wells to approximately 5 m when going south (fig. 4). It is suggested that the basinal area became almost completely filled by halite prior to the Z-3 cycle (fig. 27) (cf. Smith 1980). The difference in thickness is believed to be the result of a general rise of the chemocline during deposition. The slightly deeper lagonal areas of Tønder-2 thus faced $CaSO_4$ and NaCl sedimentation earlier than the marginal areas (Stemmerik et al. 1987).

Cored material exists from the Ca-3 unit in five of the investigated wells. Only the wells Tønder-1 and -2 and the Åbenrå-1 well were cored throughout the entire Ca-3 unit (fig. 26).

During the initial stage of Z-3 transgression, salinity levels were reduced to a degree that allowed the existence of a sparse fauna and biogene wackestones were deposited in protected lagoonal environments. Laterally, these pass into marginal marine sequences dominated by algal laminated limestone and nodular-mosaic anhydrite (fig. 26). The marginal marine and sabkha deposits prograded across the protected lagoons and as the salinity increased, carbonate deposition was restricted to the exposed areas with some circulation. In the area overlying the former basin, shallow-water conditions prevailed and deposition occured in lagoons and ponds (fig. 27). Ultimately, carbonate deposition ceased and the main part of the An-3 anhydrite and Na-3 halite was deposited in shallow-water conditions over the entire area.

A depositional model for hypersaline shelves

In a setting involving mixed carbonate/evaporite deposition, the facies and facies distribution are highly dependant on the chemocline fluctuations. Marine barriers, water circulation patterns and the climatically induced evaporation rate determine the position of the chemocline and the type of layering in the watermass. Precipitation of carbonate is facilitated by normal marine conditions that allow marine biota to become established and produce biogenic carbonate. The initial facies pattern of the carbonate deposits is controlled by the previously established relief and the associated energy and circulation pattern of seawater.

Platform developing processes deviate slightly from the normal pattern recognised for evolution of carbonate-dominated systems. When anhydrite platforms develop the extremely high sedimentation rate and the ability to aggrade effectively also in high intertidal to supratidal environments make them fast constructors of platforms with nearly flat top-surfaces. At the steep margins, gravity-driven mass-transport of sulphate sediments occurs like at normal carbonate platform margins. As an irony of fate the high accumulation rate of evaporites and especially of halite, is responsible for platform demise as the basinal area is filled.

Summary and conclusions

The Zechstein Group in southern Jylland shows a cyclic development comparable to Zechstein deposits elsewhere in the basin. In accordance with a position along the northern margin of the southern Zechstein Basin, shallow-water carbonates dominate in the northern part of the investigated area while deeper water, outer ramp and base of slope facies dominate in the Tønder Trough to the south during deposition of Ca-la and Ca-2.

Ca-la forms a carbonate wedge sloping gently to the south; the depositional pattern is in accordance with a carbonate ramp model. Ca-la is subdivided into two shallowing-upward sequences (Stentoft & Nygaard 1986) which may be correlated to similar sequences elsewhere in the basin (e.g. Paul 1986, Peryt 1986, Pöhlig 1986) and therefore are suggested to be related to regional fluctuations of sea level. Deposition of Ca-la carbonates was apparently terminated by a pronounced regression which exposed deeper parts of the basin.

During An-1 times, sea-level rose and an extensive anhydrite platform developed along the margin of the Ringkøbing-Fyn High creating as much as 400 to 500 metres of relief between the platform and the basin. This platform to basin morphology governed subsequent carbonate sedimentation when the salinity decreased due to dilution and carbonate sedimentation was reestablished at the begining of Ca-2 times. Thus shallow-water, high energy facies dominated along the platform margin and passed into low-energy facies in the protected back-barrier areas. Basinal areas were dominated by lime-mud deposition. Sedimentation appears to be aggradational as prograding wedges such as those described from Germany by Sannemann et al. (1978) have not been recorded on the seismic sections.

Later in Z-2 times the basinal areas became filled by halite thus levelling out the pre-existing topography. During the remaining part of the Zechstein southern Jylland was a relatively shallow basin dominated by anhydrite and halite deposition. The thin Ca-3 carbonate unit represents localised lagoonal deposits that interrupt this thick evaporite sequence.

The causes for the cyclicity shown by the deposits are difficult to establish. The pattern is probably a result of a complex interplay between local tectonic activity, regional subsidence, eustasy, in addition to the ability of the sediments to aggrade to sea level, purely due to high sedimentation rates. Only regionally correlatable horizons showing evidence for significant exposure or very abrupt facies-changes can be used to indicate eustatic changes of sea level.

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SERIE A · NR. 26 · Lars Stemmerik and Peter Frykman: Stratigraphy and sedimentology

This book gives a comprehensive review of sedimentology and stratigraphy in the Upper Permian Zechstein Group in Southern Denmark. The area straddles the shelf-to-basin transition on the southern flank of the Ringkøbing-Fyn High. Description of core material and petrographic investigations forms the basis for a detailed interpretation of the depositional environment recorded by the carbonate deposits. The evolution of the shelf is outlined from an initial ramp, through a platform stage, to a final shallow hypersaline intracratonic shelf. This evolutionary pattern was controlled by the dynamic progradation of evaporites, the oscillation of salinity and regional changes in sea-level.

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