Palaeobathymetry of the lower Selandian of Denmark on the Basis of foraminifera

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The palaeobathymetry of the lower Selandian sea in Denmark is studied by "departure mapping", using the foraminiferal groups Nodosariacea, arenaceous benthic foraminifera and calcareous benthic foraminifera excluding Nodosariacea, as end-members in the triangular graph. The method is discussed in view of its applicability to fossil environments. It appears that depth distribution of the superfamily Nodosariacea has changed from Palaeocene to Recent time.

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The study of foraminifera has been well established within stratigraphy for a long time and is an increasingly important tool for ecological and palaeoecological interpretations. A large number of studies on Recent foraminifera have dealt with the distribution of foraminiferal taxa in different geographical regions and ecological environments, the data primarily being used for delimiting biofacies (e.g. Walton 1955; Bandy 1956; Kaesler 1966; Ujiie & Kusukawa 1969). The distribution of the assemblages found has been compared to a variety of abiotic parameters such as temperature, salinity and substrate. Most of the studies of shelf foraminifera assemblages typically show a depth-related distribution pattern. The studies have added considerably to our knowledge of the biology of foraminifera and have further resulted in several models and methods for biofacies analysis (review by Murray 1973). In spite of a considerable demand for simple and effective methods for basin analysis in the light of palaeontological evidence, it appears that only occasional applications of a few of these models to fossil environments have been made. The present study is intended to test one of these methods, known as "departure mapping" (Upshaw & Stehli 1962), in a reconstruction of the palaeobathymetry of the lower Selandian sea in Denmark.

Material and technique

The lower Selandian is exposed at very few localities in the Danish area. The Danian-Selandian boundary has been observed only in Hvalløse (5), Klintholm (19) and in temporary excavations in the Copenhagen area. In addition to samples from these localities the present study includes material from Selandian outcrops, which are known to expose the lowermost sequence close to the Danian boundary e.g. Lellinge (26) and Klagshamn (29). Most of the material, however, derives from a large number of boreholes that include both Selandian and Danian sediments. This material, consisting of both cuttings and cores, is mainly housed in the Geological Museum, Copenhagen. A few samples have kindly been placed at the authors' disposal by the Laboratory of Micropalaeontology, University of Aarhus and by Inger Bang and B. B. Andersen of Copenhagen.

Samples were wetsieved using 63 μm sieves. Consolidated sediments were disintegrated by alternately freezing and boiling in a saturated solution of glauber salt ($NaSO_4 . 10\, H_2O$). Sample sizes varied with the material available. Most samples contained a considerable number of individuals (quite often more than 1000 specimens pr. 10 g sample) and consequently these residues were split before the specimens were counted under a binocular microscope. A minimum of 300 individuals was counted in each sample to ensure a reliable representative expression of the faunal composition. Three samples, however, contained only 247, 107 and 72 specimens; these were Wedellsborg (14), Gedser (22) and Fredericia I (13; 151 m b.s.) respectively.

Stratigraphical setting and sedimentology

The Selandian stage was proposed by Rosenkrantz (1924) for the glauconitic, calcareous and non-calcareous sediments deposited on the Upper Danian limestone and overlain by Ypresian ash layers. For a long time the age of these deposits has remained uncertain owing to a hiatus between the limestone and the glauconitic beds. The hiatus most likely arose from a regression of the Danian sea and a subsequent erosion, forming a distinct disconformity (Rosenkrantz 1924; Gry 1935; Berthelsen 1962). However, by means of foraminifera Hansen (1968) correlated the lower part of the Selandian stage to the Middle Palaeocene Angulata Zone. Hansen & Andersen (1969) suggested that the uppermost part of the Selandian non-calcareous or slightly calcareous sediments are of Upper Palaeocene age.

Gry (1935) described the lithology of the Selandian sediments in detail and a review was recently given by Dinesen et al. (1977). The basal deposits show some variation within the area studied. The sequence of the Lower Selandian transgression is initiated by relatively coarse-grained calcareous greensands, locally developed as calcite cemented basal conglomerate, rich in skeletal fragments and pebbles of Danian limestone. Upwards these basal deposits grade into light, fossiliferous marls (Kerteminde Marl) locally substituted by greensands (Lellinge Greensand). Subordinate horizons of dark pyritic clays and marls occur. The upper part of the Selandian sequence consists of slightly calcareous clays and silty deposits rather poor in fossils.

The foraminiferal fauna

The foraminiferal fauna from the Selandian strata has been described in part by Franke (1927), Brotzen (1948), Troelsen (1954), Hofker (1966), and Hansen (1968, 1970), and has most recently been discussed by Berggren & Aubert (1975). The fauna is heavily dominated by benthic representatives of the suborder Rotaliina. The Textulariina play only a very subordinate role, while the Milioliina and planktic foraminifera are practically absent. The fauna is in general well preserved and the numerical dominance of very small species (< 300 μm in test diameter) is characteristic in many samples.

The most common and characteristic taxa include the genera *Bulimina, Alabamina, Anomalinoides* and *Cibicidoides*. The superfamily Nodosariacea (sensu Loeblich & Tappan 1964) attracts attention in most samples owing to the large test sizes of individuals, but quantitatively comprises only a minor part of the total fauna.

Models for bathymetric studies

Ecological studies of foraminifera have traditionally been carried out on population analyses, species lists and single species in relation to a number of environmental parameters, e.g. depth or depth-related factors. It has been emphasized in particular that depth to some extent determines the distribution of the foraminiferal assemblages on the shelf and continental slope (Phleger 1960).

However, these kinds of studies are very time-consuming and in consequence efforts have been made to establish more simple models and methods for regional analyses.

Some of these models are established on species dominance (Walton 1964) or population studies on the basis of different diversity indices, e.g. by use of the information function (Buzas & Gibson 1969; Gibson & Buzas 1973) and the fisher-α index (Murray 1968). The use of triangular plots of suborders has been demonstrated in the description of a large number of different Recent habitats (Murray 1973).

A simple model was applied particularly for interpretation of water depth or proximity to ocean water masses on the basis of the existence of a reduction in the plankton-benthos ratio in the bottom sediments approaching the shore line (Murray 1976, and references herein).

A similar but improved model for depth analysis, the "departure mapping", was proposed by Upshaw & Stehli (1962) who tested it on data from continental shelf environments in the Mexican Gulf (Bandy 1956). Three major foraminiferal groups: planktic, calcareous benthic and arenaceous benthic foraminifera, were shown to have distinctive and different

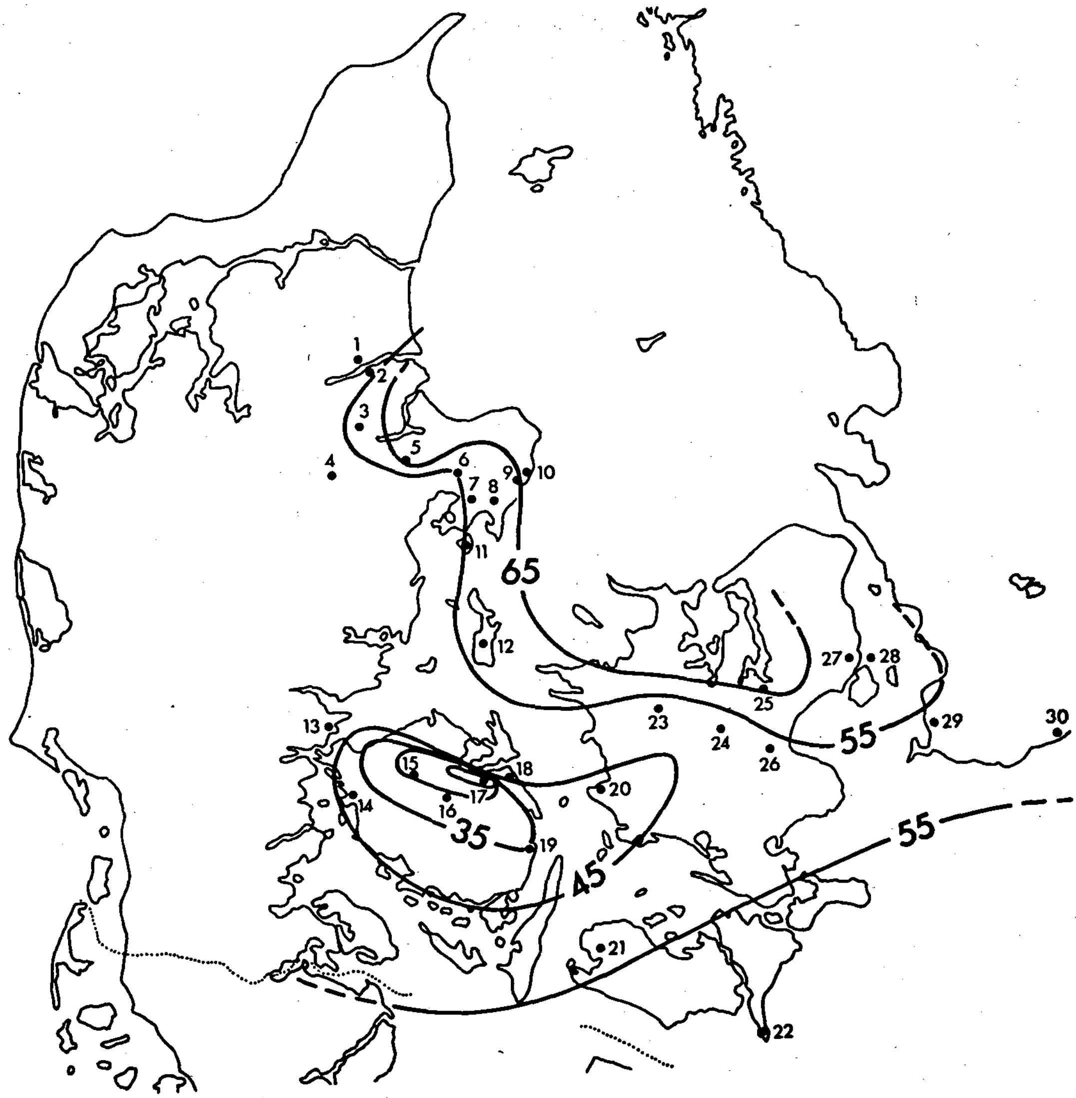

Fig. 1. Map indicating position of localities (marked by numbers) and iso-departurelines reflecting the bathymetry of the Selandian sea.

depth distributions in the region studied. It follows that a specific depth hereby is characterized by a certain percentual proportion of the three groups. By plotting these proportions from a large number of localities in a triangular graph it was possible to reconstruct basin morphology. The principle in the reconstruction was that a linear departure from a selected "target environment" in the graph reflected a bathymetric deviation in nature.

Analytical technique

In this study the "departure mapping" method was applied to Danish Selandian deposits.

The composition of the lower Selandian foraminiferal fauna as described above does not allow a "departure mapping" in the sense of Upshaw & Stehli (1962) due to the near absence of planktic foraminifera. An obvious solution to this problem is the selection of other foraminiferal groups as endmembers in the triangular plot. Such a modification may be tolerated only on the assumption that there exists a distinctive and different depth distribution of the newly established foraminiferal components.

The superfamily Nodosariacea (sensu Loeblich & Tappan 1964) particularly attracts attention since it is an important faunal element in conglomerates and coarse-grained sandstones of assumed near coastal facies (cf. the Hvalløse conglomerate (5) and Ystad 6 (30)) in contrast to its rather sporadic appearence in marls and silty sediments. Furthermore the Nodosariacea forms a characteristic and easily recognizable part of the fauna. For these reasons the Nodosariacea was introduced as a substitute for the planktic foraminifera in the original model of Upshaw & Stehli (1962). Thus the present study implies a succession of Nodosariacea, arenaceous and calcareous benthic foraminifera (excluding Nodosariacea) from shallow towards deeper water.

Localities comprising lower Selandian (Middle Palaeocene cf. Dinesen et al., 1977) were included in the investigation. 30 outcrops and boreholes were found to serve this purpose (table 1 and fig. 1). In order to obtain optimal stability of the Selandian palaeogeography under examination sampling was undertaken in stratigraphically narrow sequences, and samples were collected as close to the base of the Selandian as possible. However, the basal coarse-grained greensand and conglomerate themselves were not sampled in order to avoid their obviously transgressive phase. Furthermore five vertical sections: Hvalløse (5), Rugård (10), Fredericia I (13), Copenhagen TUBA 13 (27) and Ystad 6 (30) were studied in order to reveal the vertical composition of the foraminiferal fauna.

The percentage ratios between the three foraminiferal groups were plotted for each sample in a triangular graph (fig. 2). The sample that, according to lithological evidence, represented the shallowest environment (the Hvalløse conglomerate (5)) was selected as "target en-

LOCALITY		%			DEPARTURE
NR.	NAME	CB	N	A	UNITS
1	Skovbo	92.3	6.9	0.8	58
2	Katbjerg	80.9	3.3	15.8	54
3	Svejstrup	92.0	6.4	1.6	58
4	Langå	72.7	16.3	11.0	32
5	Hvalløse				
	congl.	61.9	34.5	3.6	0
	0–15 cm a.D.	88.8	9.9	1.3	52
	15–30 cm a.D.	91.8	7.6	0.6	57
	* 30–45 cm a.D.	96.3	2.6	1.1	66
	45–60 cm a.D.	97.1	2.1	0.8	68
	60–75 cm a.D.	97.0	3.0	0.0	67
	75–90 cm a.D.	95.8	2.9	1.3	66
	90–105 cm a.D.	96.2	3.7	0.1	65
	105–120 cm a.D.	96.1	3.2	0.7	66
6	Korup	88.7	6.8	4.5	55
7	Basballe	91.7	5.1	3.2	59
8	Egsmark	87.9	7.2	4.9	53
9	Jernhatten	93.4	5.8	0.8	60
10	Rugård				
	26.5 m b.s.	94.1	1.6	4.3	65
	* 26.0 m b.s.	97.7	1.1	1.2	69
	18.0 m b.s.	98.8	0.9	0.3	71
	12.0 m b.s.	98.4	1.6	0.0	70
	5.0 m b.s.	98.4	1.6	0.0	70
11	Tranebærgård	90.0	7.7	2.3	55
12	Besser	91.0	7.0	2.0	57
13	Fredericia I				
	* 167 m b.s.	90.1	9.5	0.4	53
	165 m b.s.	89.4	10.3	0.3	52
	163 m b.s.	92.2	7.7	0.1	57
	161 m b.s.	91.9	7.8	0.3	57
	151 m b.s.	93.0	7.0	0.0	59
14	Wedellsborg	82.0	15.0	3.0	40
15	Sværup	71.9	23.8	4.3	21
16	Dalum	77.7	20.1	2.2	30
17	Ulriksholm	67.2	26.6	6.2	14
18	Lundsgård	86.0	10.8	3.2	48
19	Klintholm	74.5	14.3	11.2	35
20	Bjørnskilde	82.1	14.7	3.2	40
21	Tårs	88.2	10.9	0.9	50
22	Gedser	0.0	0.0	100.0	169
23	Hanerup	89.1	8.9	2.0	53
24	Hvalsø	87.1	12.0	0.9	48
25	Roskilde	97.0	2.4	0.6	67
26	Lellinge	90.0	9.7	0.3	53
27	Tuba 13				
	10 cm a.D.	92.2	6.9	0.9	58
	25 cm a.D.	94.9	4.3	0.8	63
	45 cm a.D.	95.6	3.6	0.8	65
	* 75 cm a.D.	94.0	4.8	1.2	62
	110 cm a.D.	94.8	4.8	0.4	63
	120 cm a.D.	93.4	6.0	0.6	60
	190 cm a.D.	92.4	6.8	0.8	58
	230 cm a.D.	94.0	4.3	1.7	62
28	Prøvestenen	93.3	4.8	1.9	61
29	Klagshamn	90.3	8.9	0.8	54
30	Ystad 6				
	1.2 m a.D.	91.1	8.1	0.8	56
	1.7 m a.D.	95.0	4.3	0.7	64
	* 3.0 m a.D.	87.5	11.0	1.5	49
	4.4 m a.D.	65.0	27.8	7.2	12
	4.7 m a.D.	90.1	8.6	1.3	54
	6.1 m a.D.	78.0	20.0	2.0	31
	6.7 m a.D.	83.4	13.9	2.7	42

*Table 1. Localities, percent composition of foraminiferal fauna and calculated departure units. CB: Calcareous benthic foraminifera excluding Nodosariacea. A: Arenaceous foraminifera, N: Nodosariacea, congl: conglomerate, a.D.: above Danian, b.s.: below surface, *: the sample in the section used in reconstruction of the Selandian structure.*

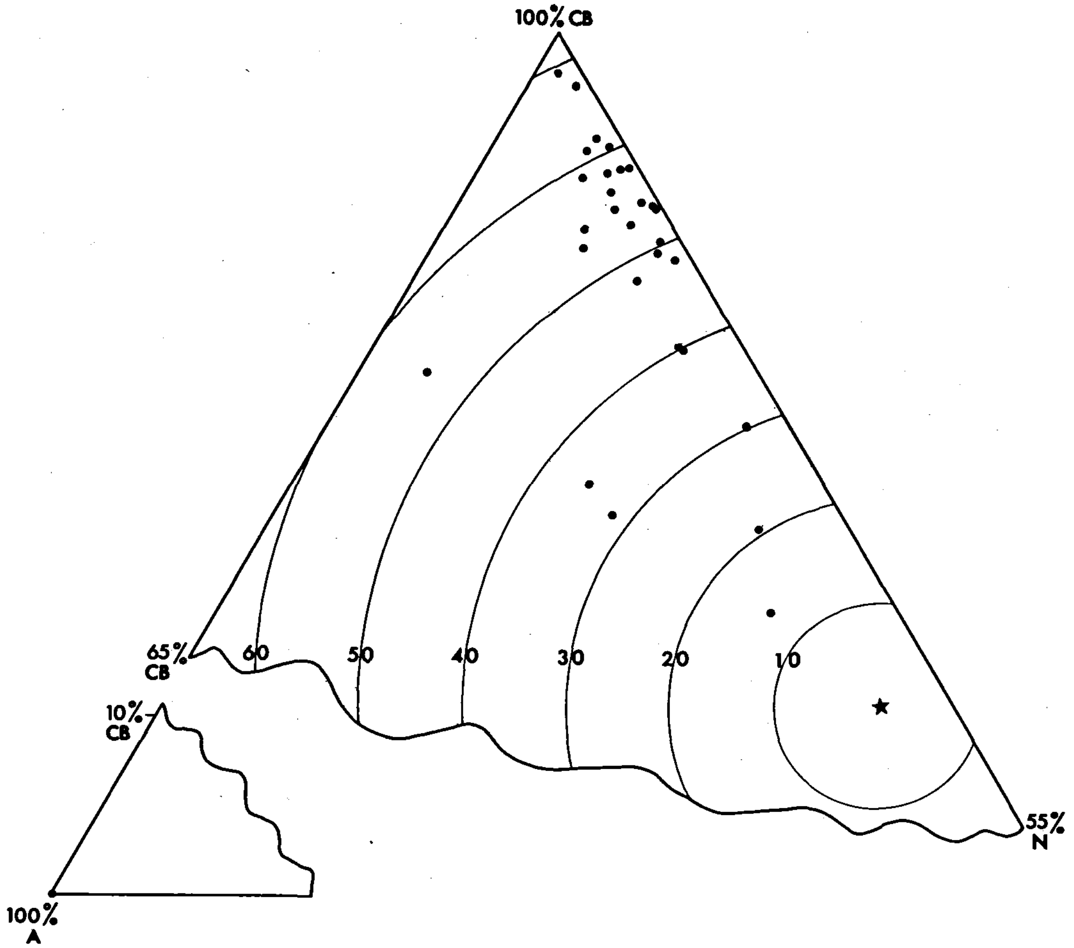

Fig. 2. Triangular graph from which departure units can be obtained. •: composition of foraminiferal fauna in the target environment (5, Hvalløse conglomerate). Composition of assemblages used in the reconstruction of the Selandian structure (fig. 1). CB: calcareous benthic foraminifera excluding Nodosariacea, A: arenaceous foraminifera, N: Nodosariacea.

vironment" and the distance in departure units, arbitrarily chosen, was measured to each locality. Finally a contour map with iso-departure lines was constructed on the basis of the departure values of each locality (fig. 1).

In practice the measure of distance in the triangular graph from the "target environment" to each of the remaining localities was determined by a computer.

For this purpose the parameters of any point in the triangular graph was transformed to a conventional x/y coordinate system (fig. 3). Simple geometrical considerations determine the new parameters as $X = \frac{\frac{CB}{2} + N}{\cos 30}$; $Y = CB$.

(CB: Percentage benthics excluding Nodosariacea; N: Percentage Nodosariacea). The distance between two points is determined by D =

$$\sqrt{\left(\frac{\frac{CB_2}{2} + N_2}{\cos 30} - \frac{\frac{CB_1}{2} + N_1}{\cos 30}\right)^2 + (CB_2 - CB_1)^2}$$

Use of a small computer and this formula does in fact render the plotting of samples in the triangular graph superfluous. It should only be remem-

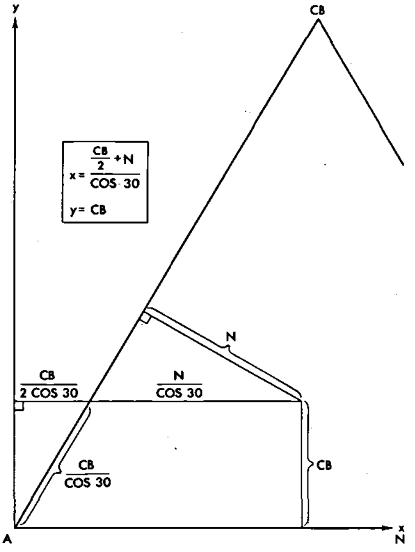

Fig. 3. Triangular graph showing how a point in the triangular graph is transferred to a x/y coordinate system. CB, A and N as in fig. 2.

bered that the unit used in measuring the distances becomes the same unit as that used for measuring percentages. If for some reason another unit should be desired, correction for this can easily be added.

Results

As previously discussed the basal conglomerate in the Hvalløse section (5) was selected as "target environment" supposedly representing the most shallow environment of all samples studied. The localities, calculated percentages and their respective departure values in comparison to "target environment" are shown in table 1. The corresponding triangular graph is given in fig. 2.

The contour map (fig. 1) shows a pronounced area of relatively low departure values (10–35) centered on the island of Fyn. The iso-departure lines indicate an area of rather high departure values (55–70) in a region from the eastern part of Jylland to the Copenhagen area. Furthermore, the departure values obtained from the two Swedish localities, Klagshamn (29) and Ystad (30), indicate slightly decreasing tendency (54–49) in the eastern part of the area under study.

One locality only, Gedser (22), shows a distinct deviation from the general pattern given above, indicating unusual environmental conditions.

The vertical distribution of the three foraminiferal groups shows a characteristic variation within the sections studied (fig. 4). The largest content of Nodosariacea was found in the basal conglomerate at Hvalløse. The strata immediately above display a rapid decrease in contents of Nodosariacea resulting in rising values of departure units. However, a minor but distinct decrease in departure values in the upper part of the Hvalløse section occurs. Similar tendencies are found in corresponding levels in the sections of TUBA 13 and Ystad 6.

The faunal composition expressed in departure values shows only a rather vague variation in the sections of Rugård and Fredericia I.

Interpretation and discussion

The sporadic appearance of planktic foraminifera and Milioliina in the material studied points to an isolation of the Danish Selandian sea from oceanic water masses, and possibly to a salinity below that of normal oceanic conditions.

The Palaeocene foraminifera from Denmark and Sweden reveal affinity to the so-called "Midway fauna", which is regarded as: "a middle to outer shelf assemblage (50–200 m water depth) developed in a shale-marl environment." (Berggren & Aubert 1975). The use of a model based on shelf faunas (e.g. the departure mapping) agrees well with this general concept of shelf-like conditions in the Selandian sea.

The use of Nodosariacea as shallow water indicator does not apply to Recent distribution of this superfamily. The comprehensive material from the shelf off NW Florida (Bandy 1956) also contains information about the Nodosariacea, showing a depth distribution with a quantitative maximum at approximately 130 m. However, the Nodosariacea is a subordinate group, never exceeding 5 percent of the entire foraminiferal fauna. It appears that the Nodosariacea today is a rather unimportant element in the shelf fauna, being generally more abundant in deeper water. Nevertheless, the present study leaves no doubt

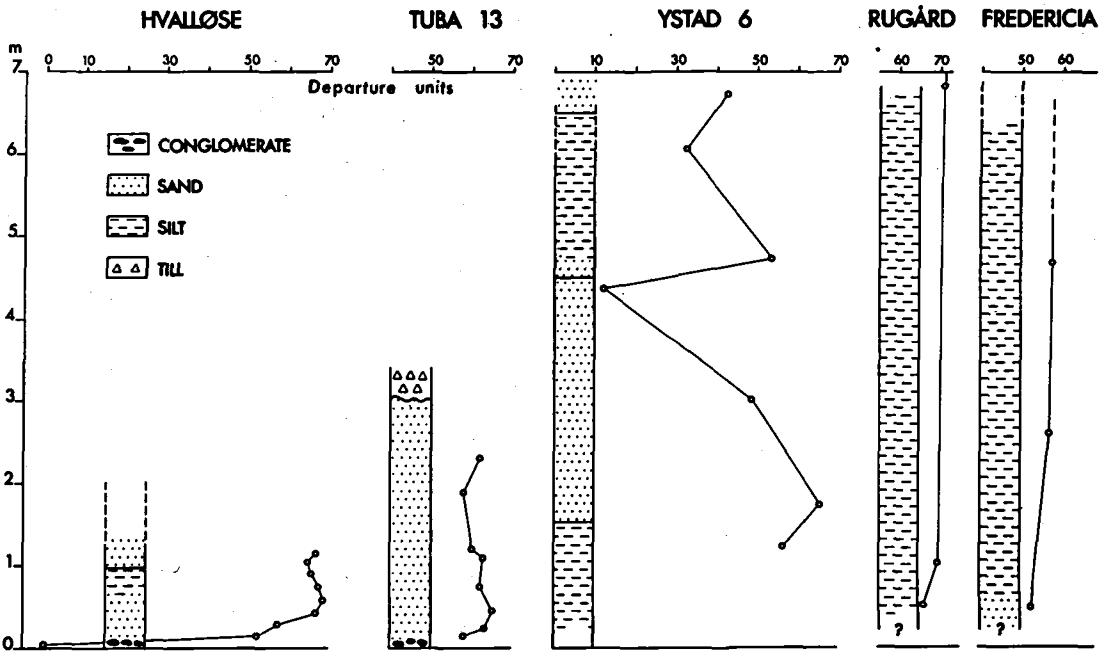

Fig. 4. Lithology and departure units in different levels of the sequences examined. Vertical axis: level above Danian. Horizontal axis: departure units indicated by the composition of the foraminiferal fauna.

that the Nodosariacea was a charateristic group in the Selandian sea, particularly in shallow-water environments (see fig. 4 and table 1: the Hvalløse and Ystad 6 sections). A possible explanation for the post-Selandian environmental displacement can be seen in the light of the success of symbiont-bearing benthic foraminifera, which in present-day seas are important in shallow-water environments.

Regarding the arenaceous foraminifera, the absence or near absence of these in a considerable number of the samples falls outside the theoretical composition suggested from the Recent model. This last observation however, is believed to be due to a bias in the material examined. It is obvious that arenaceous foraminifera are very much exposed to decomposition after death in their original environment as well as during the processing of samples in the laboratory (Brodniewicz 1965).

One locality only, Gedser (22), contains a purely arenaceous fauna, which cannot be regarded as a typical shelf fauna. The reason for this must be found outside the framework of the model. Using the triangular plots presented by Murray (1973) the most likely interpretation of the faunal composition would be its derivation from marsh environmets. Unfortunately the locality has a marginal postition in the area studied and the present materiel does not furnish us with any other indications.

Since the primary aim of this study has been to test the method of "departure mapping", it is considered important that main structures well known from an appreciable span of geological time are recognizable from the result. However, more detailed structure of the Selandian basin is incompletely known. Some information can be obtained from a study of the facies distribution (Spjeldnæs 1975). Also the present-day topography of the Danian surface can be used for making interpretations about the Selandian sea. Data useable for such analyses have been published by Dinesen et al. (1977) and Andersen & Tychsen (1976). Problems connected with this kind of approach towards interpretation of ancient structures mainly concern the obliterating effect of post-Selandian tectonic movements.

Moreover, it should be remembered that the Danian surface in general represents an erosional surface the age of which is not known.

The material used in the present study is not biased by post-Selandian earth movements, but there is nevertheless considerable uncertainty about the period of time represented by the material.

Generally speaking, biostratigraphic correlation of samples is accepted when making basin analyses, even though this often implies a claim of stability in the basin during an appreciable period of time (1 my or more). The interval between the Danian and the Ypresian comprises a period of approximately 6 my and can be divided into three biozones by use of planktic foraminifera (cf. Berggren 1972).

A biostratigraphy of the Selandian strata does not exist and the time span represented by the Selandian deposits is unknown. Efforts have been made in the present study only to include samples from the lower part of the Selandian sequence with the purpose of reducing the time interval considered. The lack of a well established biostratigraphic correlation of the material is unfortunate. However, even within a biozone representing 2 my it would be necessary to require a certain stability of the geomorphological structure studied.

The most obvious structure revealed is the significant high in the Fyn area (fig. 1). A high in this area is a well known structure which is traceable back to Late Palaeozoic (cf. Ziegler 1975). Dinesen et al. (1977) showed that this high was reflected by the Danian surface. Equally, the isopach map of the Danian from the NW European continental shelf published by Pegrum et al. (1975) demonstrated the existence of this high as an important structure in the Danian sea. Studies of isopach maps and contour maps (Pegrum et al. 1975; Dinesen et al. 1977) indicate that the western part of the Ringkøbing-Fyn High has been affected by a higher degree of subsidence than the eastern part during the Tertiary period. The existence of the Ringkøbing-Fyn High in the Selandian with a submerged western part is indicated by this study.

The samples from the section at Hvalløse represent the most complete sequence of the lowermost part of the Selandian strata (fig. 4). The unconsolidated conglomerate from Hvalløse made it possible to carry out a quantitative examination of the foraminiferal fauna in contrast to what was feasible in the carbonate cemented conglomerate in the TUBA 13 borehole.

The rapid increase in departure values in the lowermost part of the Hvalløse profile indicate a distinct change in the faunal composition contemporary with the progressing transgression. This trend strongly supports the utility of the model used in this study.

The Ystad section appears, from a sedimentological point of view (fig. 4), to have been deposited close to the margin of the Selandian sea. The strongly fluctuating departure values reflect the particular sensitivity of the method in the marginal parts of the sea. According to the model the slight decrease of departure values in the sequences above the basal deposits at Hvalløse, TUBA 13 and Ystad 6 indicates a minor shallowing of the sea. The different levels of these departure-value minima in the profiles indicate decreasing sedimentation rates from Ystad 6 *via* TUBA 13 to Hvalløse. The departure values from the lowermost samples situated above the basal conglomerate at Ystad 6 and TUBA 13 sections reflects the termination of the initial Selandian transgression.

The sections from Hvalløse, TUBA 13, Rugård and Fredericia I all point to a relative stability of depth conditions following the major transgression. Maximum deviation is found in the TUBA 13 section. The final palaeogeographical map (fig. 1), however, would not be altered significantly even if the most deviating sample from above the transgression were used in the reconstruction.

The apparent depth stability in the more central parts of the basin strongly indicates that the structure found represents a reasonable approximation to the Selandian basin. The lack of confirmed isochrony between the samples seems to be unimportant in the present case since it is counteracted by the apparent stability of the structure examined.

Conclusions

Upshaw & Stehli (1962) emphasized two important conditions for the use of their method: (1) samples must not be contaminated with material from different stratigraphical levels, and (2) correlation in time must be established between the incorporated samples. The material used in this study gives no reason to believe that the first condition is not fulfilled. Correlation in time, though, leaves much to be desired, since it is based on lithostratigraphic evidence. However, Upshaw & Stehli's second condition could also be modified to: "The structure examined must have been stable within the period considered". The sections studied do indicate a reasonable stability after the main transgression (fig. 4). Thus from this point of view it becomes probable that the major structural features found would not be changed significantly, even if a biostratigraphic correlation could be established. Major fluctuations are found in coastal areas where they were to be expected (cf. Ystad 6).

Other important conditions are that: (3) the material must be well preserved and represent the original faunal composition; (4) localities included must be geographically well distributed in the area under consideration and (5) no other environmental factor than depth (or depth related parameters) must act so strongly that it blurs the depth related effect on the faunal composition.

The fauna in the present study is well preserved. However, the arenaceous foraminifera do not appear to occur in such numbers as would be expected according to the Recent model. This might be a good reason to chose a different endmember when working with fossil material. The faunal composition and distribution in the studied area leaves no reason to doubt that the iso-departure lines reflect a depth related pattern. Only on locality, Gedser (22), exhibits a faunal composition that must be explained by other environmental parameters.

In spite of the reservations made above, the presented bathymetric outline of the Selandian sea represents a reasonable suggestion of this ancient structure. However, the general application of the method to palaeoenvironmental investigations implies further studies. In particular it should be recommended to test the model on well known fossil structures.

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Dansk sammendrag

Palæobathymetrien og bassinstrukturen i det nedre Selandian hav er undersøgt ved hjælp af "departure mapping" metoden. Metoden bygger på den dybdeafhængige variation i den kvantitative sammensætning af foraminiferfaunaen på shelfområderne og er oprindelig opstillet og testet på Recent materiale (Upshaw & Stehli 1962). I den foreliggende undersøgelse er benyttet det kvantitative forhold mellem agglutinerende foraminiferer, Nodosariacea og kalkskallede bentoniske foraminiferer eksklusive Nodosariacea fra et større antal lokaliteter og boringer omfattende Selandian bjergarter i det danske og sydsvenske område.

Undersøgelsen tegner beliggenheden af Ringkøbing-Fyn højderyggen i nedre Selandian tid (Mellem Pàleocæn) og indicerer en mulig kystlinie i området omkring Ystad (Sverige). Modellens anvendelighed på fossile strukturer diskuteres i lyset af den foreliggende undersøgelse.

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