RW

MEDDELELSER FRA DANSK GEOLOGISK FORENING · BIND 26 · HÆFTE 3–4

Bulletin of the Geological Society of Denmark

Volume 26 · part 3–4
Copenhagen 1977

Bulletin of the Geological Society of Denmark

Volume 26 · part 3–4

The Bulletin carries papers dealing with all fields of geological science, with a natural emphasis on results of new work on material from Denmark or Greenland. The Bulletin is published in English (preferred language), German or French, and receives financial support from the Danish Natural Science Research Foundation. One volume of four parts is published each year.

Geological Society of Denmark

(Dansk Geologisk Forening)
founded in 1893

Membership fee for 1977: 100.00 Danish kroner.

All members will receive volume 26 of the Bulletin and a Yearbook (Årsskrift, normally printed in Danish). Send request for personal membership to: The Treasurer, Geological Society of Denmark, Øster Voldgade 5, DK-1350 København K.

Members can purchase previously issued volumes or single parts at a reduced rate through the Society. Non-members or institutes can order all published volumes or single parts, provided that they are not out of print, from: C. A. Reitzel (Publisher), Nørre Søgade 35, DK-1370 København K.

Editor: Richard Bromley
Institut for historisk Geologi og Palæontologi
Øster Voldgade 10, DK-1350 København K.

Authors alone are responsible for the scientific content of their contributions.
Instructions for contributors appear inside the back cover of every part.

Authorised abbreviations:
Meddelelser fra Dansk Geologisk Forening (i.e. vol. 1–18) = *Meddr dansk·geol. Foren.*
Bulletin of the Geological Society of Denmark (vol. 19 onwards) = *Bull. geol. Soc. Denmark*

MEDDELELSER FRA DANSK GEOLOGISK FORENING · BIND 26

Bulletin of the Geological Society of Denmark

volume 26

1977

ANDELSBOGTRYKKERIET I ODENSE

Volume 26 (1977)

Editor: Richard Bromley

Contents

Morphological variability and temporal change in a Paleocene lucinid bivalve mollusk

SARA S. BRETSKY and ERLE G. KAUFFMAN

Bretsky, S. S. & Kauffman, E. G.: Morphological variability and temporal change in a Paleocene lucinid bivalve mollusk. *Bull. geol. Soc. Denmark*, vol. 26, pp. 161–174. Copenhagen, December 1st 1977.

Analysis of morphological variability, using six characters, in four stratigraphically successive populations of the lucinid bivalve mollusk *Myrtea (Gonimyrtea) uhleri* shows a unidirectional trend toward decreasing mean size. Differences in mean length for stratigraphically adjacent populations are significant at the 5% level of probability. Chronoclinal trends toward decreased magnitude of apical angle measurements and of increased magnitude of two form ratios associated with apical angularity can be explained by a tendency toward increase with growth in the quadrateness of the shell. Thus, populations of smaller mean size are also on average more trigonal. The observed decrease in mean size is associated with marine regression in the study area (Paleocene Brightseat and Aquia Formations of Maryland and Virginia, U.S.A.). Earlier representatives of the species are more common in an offshore facies, and later ones are more common in a nearer-shore but still subtidal one. Comparing specimens from nearshore and offshore facies without regard to stratigraphic position shows a statistically significant difference in size; the nearshore specimens are nearly 20% smaller, on average, than the offshore ones. Possible contributors to the size decrease may have been a slowdown of growth rate in the physically more rigorous nearshore facies; an increased probability of mortality at earlier ages in episodic sedimentation events, expected to occur more frequently nearer shore; or selection for accelerated maturation in more rigorous and unpredictable environments.

Sara S. Bretsky, Department of Earth and Space Sciences, State University of New York, Stony Brook, New York 11794, U.S.A. Erle G. Kauffman, Department of Paleobiology, U. S. National Museum, Washington, D. C. 20560, U.S.A. *January 8th, 1977.*

As part of a study of the systematics of lucinacean bivalve mollusks of Paleocene age from the North American Coastal Plain, we have carried out a detailed morphological analysis on the longest-ranging and best-preserved species of these, one whose fossil record in the study area spans some 7 to 8 million years (Hazel 1969). We have observed an apparent 'chronocline', a decrease in mean size with consequent changes in some aspects of shape, which coincides with a shift in the habitat of the species, associated with an overall trend toward marine regression.

Geologic setting

Approximately 900 specimens of the small lucinid bivalve *Myrtea (Gonimyrtea) uhleri* (Clark 1895) were obtained from the Paleocene Brightseat and Aquia Formations in the Middle Atlantic Coast region. These specimens came from a total of 40 different, closely spaced stratigraphic levels at 11 geographic localities in the Potomac River Valley (figs 1 & 2). Fig. 2 provides a generalized stratigraphic section for the Brightseat and Aquia Formations in this region, indicating the portions of the section in which the species is most common. Descriptions of collecting localities and sampling horizons, and a breakdown by samples of the abundance of *M. (G.) uhleri*, are available on request, and will appear in a formal systematic treatment of the Potomac Valley lucinaceans (Kauffman & Bretsky, in preparation).

The Brightseat and Aquia Formations in the Potomac River Valley comprise a sequence of unconsolidated to partly lithified, dark greenish-gray quartz or quartz-glauconite sands, with some admixtures of silt and clay (Kauffman & Beauchamp 1969; Kauffman & Bretsky, in preparation). Micropaleontological evidence (Berggren 1965; Hazel 1968, 1969) indicates that these strata represent about 7 to 8 million years, including an apparent gap of some 3 million years' duration between Brightseat and Aquia deposition. The lithology and macrofossils of the two formations, as opposed to the microfaunas, are, however, broadly quite similar (Beauchamp

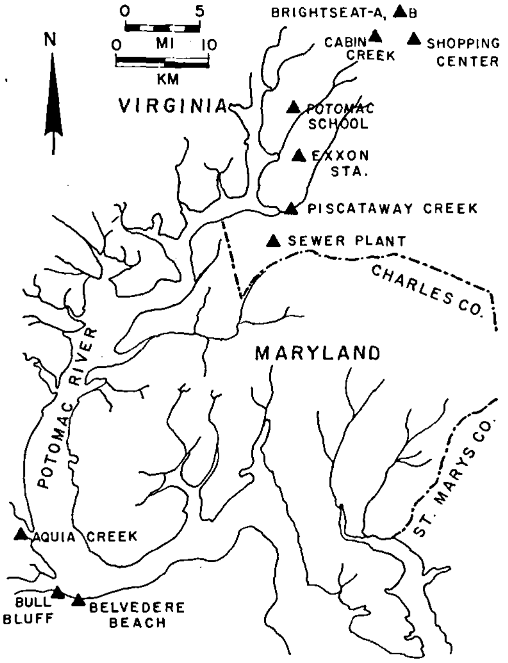


Fig. 1. Locality map indicating sites where specimens of Myrtea (Gonimyrtea) uhleri *were obtained. Locality 'Brightseat A, B' corresponds to original type locality of Brightseat Formation ('Brightseat A'), now poorly exposed, and nearby reference section ('Brightseat B').*

1969). In particular, the species with which we are here concerned, *Myrtea (Gonimyrtea) uhleri*, has been recorded from the lowest to the highest stratigraphic level of our collections from the combined Brightseat and Aquia Formations. Individual specimens from the two formations cannot be discriminated by any feature of dentition, sculpture, or musculature. Although the record of *M. (G.) uhleri* spans the full Brightseat-Aquia sequence of deposition, the species is distinctly more common in, though not exclusively confined to, certain portions of the lithofacies and paleoecological settings which make up these formations.

Biology of *Myrtea (Gonimyrtea) uhleri*

Lucinid adaptations

Myrtea (Gonimyrtea) uhleri is a member of the Family Lucinidae. In the context of the present study, the most salient points of the inferred biology of *M. (G.) uhleri* are its infaunal habit (fig. 3), its communication with the water column via an anterior inhalant tube constructed of sediment grains, the control of its depth of burial by the maximum extensibility of the foot, and the probability that it, like living lucinids, was a very sluggish burrower (Allen 1958; Stanley 1970). These last two points suggest that either disinterment or burial beneath an influx of sediment exceeding some critical thickness would likely have had fatal results. The relevance of this supposition appears later with documentation of an apparent change of habitat preference of *M. (G.) uhleri* from a more offshore to a more nearshore environment. Another potential source of mortality, the attacks of shell-boring gastropods, appears to have remained constant at about 15% of the total sample of specimens from each sort of habitat.

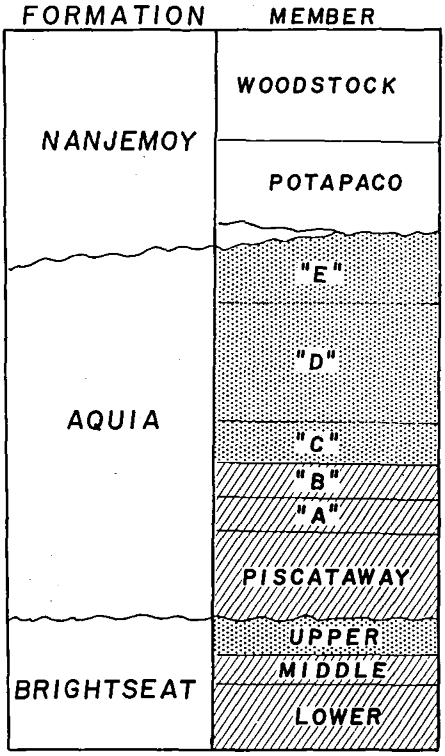


Fig. 2. Stratigraphy of Paleocene to Middle Eocene sediments in the Potomac River Valley. Nomenclature of members of the Brightseat and Aquia Formations follows an informal system pending a more formal proposal by Kauffman & Beauchamp (in preparation). Pattern of diagonal lines indicates Brightseat and Aquia units in which M. (G.) uhleri *is common; dotted pattern indicates those in which it is present but rare. Total thickness of exposed Brightseat and Aquia in the region is about 100 feet.*

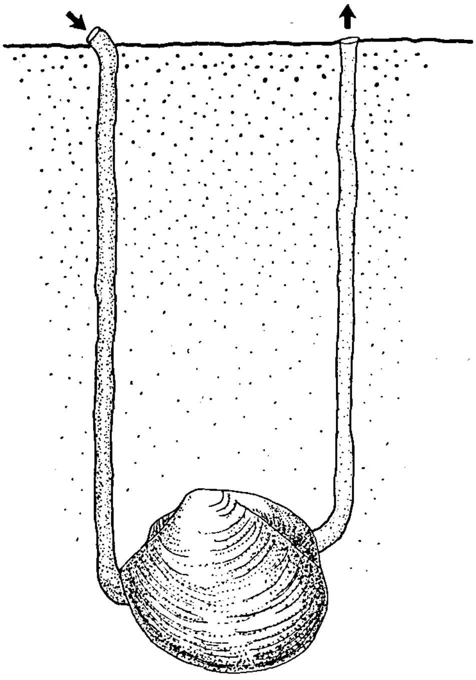


Fig. 3. Living position of a generalized lucinid (after Allen 1958). Arrows indicate location of anterior inhalant current, entering through feeding tube, and of posterior exhalant current, exiting through siphon. Not to exact scale; depth of burial of animal is typically 6 to 10 times height of shell.

Brightseat-Aquia paleoecology

One of us (EGK) has reconstructed the major features of Paleocene paleoecology in the study area on the basis of evidence from sediment type, macropaleontology, and physical and biogenic sedimentary structures (fig. 4). Our data on the occurrences of *Myrtea (Gonimyrtea) uhleri* within this paleoecological framework (Kauffman & Bretsky, in preparation) indicate that this species, like many other fossil lucinids (Bretsky 1976) but unlike the great majority of living lucinids which have been studied from an anatomical or ecological viewpoint (Allen 1958; Jackson 1973) preferentially inhabited a subtidal rather than an intertidal environment.

In a broad sense, Paleocene sedimentation in the Potomac River Valley records a regional regressive trend, but superimposed on this major trend are four shorter-term cycles of deepening and shallowing of the Paleocene sea. In each cycle of sedimentation the four onshore-to-offshore facies diagrammed in fig. 4 appear to have been represented. We have found specimens of *M. (G.) uhleri* in sediments of all four facies, but only rarely in the most nearshore one.

In the Brightseat Formation and in the lower part of the Aquia, *M. (G.) uhleri* is common in an offshore assemblage made up mostly of species of rather small size (individuals generally less than 3 cm long). This assemblage is generally characteristic of Facies 3 (fig. 4), a silty quartz-glauconite sand. In this part of the section *Myrtea* is also found in the most offshore, most clayey and least glauconitic facies (Facies 4, fig. 4), an environment characterized by low diversity and low abundance of shell-bearing organisms, but one in which the sediments are highly burrow-mottled. This setting may have been like those Recent occurrences which are unfavorable for most suspension-feeding organisms because of the presence of a zone of gill-clogging suspended organic detritus above the sediment-water interface (Rhoads 1974). It may, however, have been less inimical to *M. (G.) uhleri* if this species shared the common lucinid adaptations of tolerance of anaerobic conditions and ability to process large-sized detrital particles (Jackson 1973).

Another assemblage of which *M. (G.) uhleri* is a common member, more so in the upper part of the Aquia than in the Brightseat and lower Aquia (Facies 2, fig. 4), typically occurs in a fine-grained quartz-glauconite sand representing nearshore, but still subtidal, deposition under conditions of intermittently high wave and current activity. Organisms in this assemblage generally belong to larger-sized species, and faunal diversity is higher, than in the assemblage characteristic of Facies 3.

Table 1 documents a shift through time in the occurrence of *M. (G.) uhleri* relative to sedimentary facies (fig. 4 portrays this change diagrammatically). In the Brightseat and the lower part of the Aquia, the species is most common in sediments of Facies 3, but is also relatively well represented in both Facies 2 and Facies 4. In the upper part of the Aquia it is most abundant in Facies 2, less so in Facies 3, and rare in Facies 4. In neither case, however, does it have more than occasional representation in the nearest-shore regime. The more nearshore Facies 2 itself becomes more commonly rep-

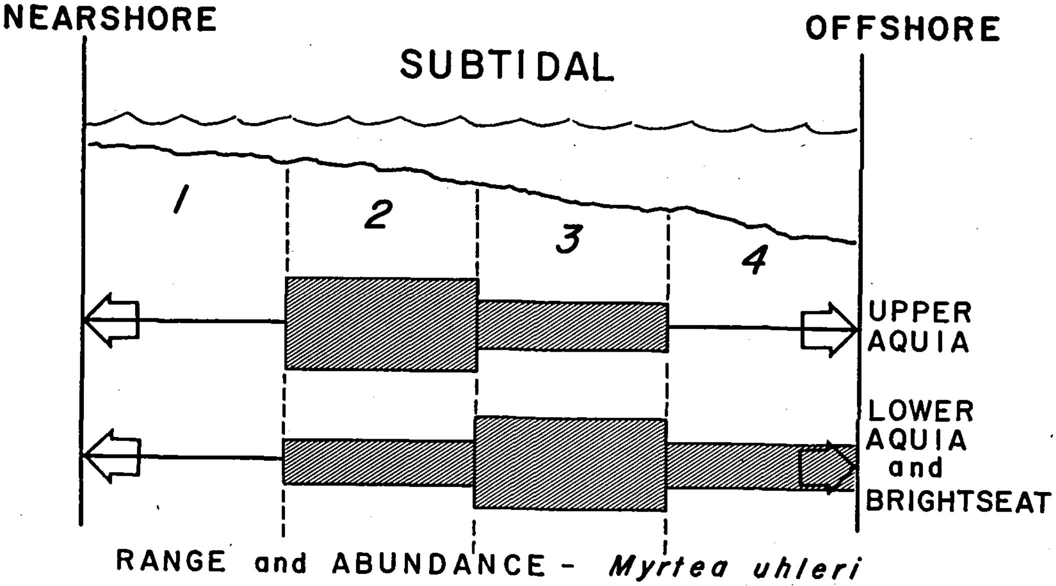


Fig. 4. Schematic reconstruction of Brightseat and Aquia paleoenvironments. Numerals correspond to four principal onshore-to-offshore facies, as follows: 1-indurated sandstone; glauconite about 40%; macrofossils abundant, heavy-shelled, usually more than 3 cm long, showing evidence of orientation by strong wave and current activity; species diversity low. 2-poorly indurated sands; glauconite about 40%; macrofossils abundant, usually more than 3 cm long often occurring in storm-laid shell beds; species diversity high; cross-bedding and Callianassa *burrows common. 3-sands and sandy silts; glauconite about 30%; clay 10% or less; macrofossils locally abundant and diverse, usually less than 3 cm long, not transported. 4-silty sands and sandy silts: clay 10–15%; glauconite 5% or less; macrofossils not abundant or diverse; highly burrow-mottled. Double-headed arrows indicate range of* M. (G.) uhleri, *with width of bar roughly proportional to abundance of the species in a particular facies (thin line indicates that the species is present but rare). Bulk samples totalling approximately one cubic meter of sediment per horizon were collected at each of some 60 horizons (40 of which yielded specimens of* M. (G.) uhleri).

resented in the upper part of the section, as the general regression of the Paleocene sea proceeds.

Morphometric methods

Counts and measurements

On the basis of breaks in the abundant occurrence of *Myrtea (Gonimyrtea) uhleri* which correspond to obvious lithological changes within the Brightseat and Aquia Formations, we have defined four stratigraphically-separated 'collections' of the species (fig. 2). All the Brightseat specimens are considered together, because 80% of the complete individuals from this formation come from a single 2-foot-thick interval at one locality (Shopping Center, fig. 1) where the boundaries of the middle Brightseat member are not well defined. We have three groups of specimens from the Aquia Formation. The lowest of these is from the Piscataway Member, which immediately overlies the Brightseat; the two others are from strata here informally designated as Member A and Member B (fig. 2).

These four groups of specimens, each of which includes enough well-preserved material to permit the carrying out of detailed morphometric analyses, are linked by the occurrence of occasional specimens (sometimes present only as fragments of valves) of *Myrtea* in what were presumably less favorable environ-

Table 1. Sedimentary facies and occurrences of specimens of *Myrtea (Gonimyrtea) uhleri.*

Stratigraphic unit	Specimens Counted	Percentage of specimens occurring in Facies 4	Facies 3	Facies 2
Brightseat	520	7.1	82.5	10.4
Piscataway	209	0	46.4	53.6
Member A	82	0	100	0
Member B	68	0	0	100
Member C	1	100	0	0
Member D	11	0	0	100
Member E	6	0	0	100

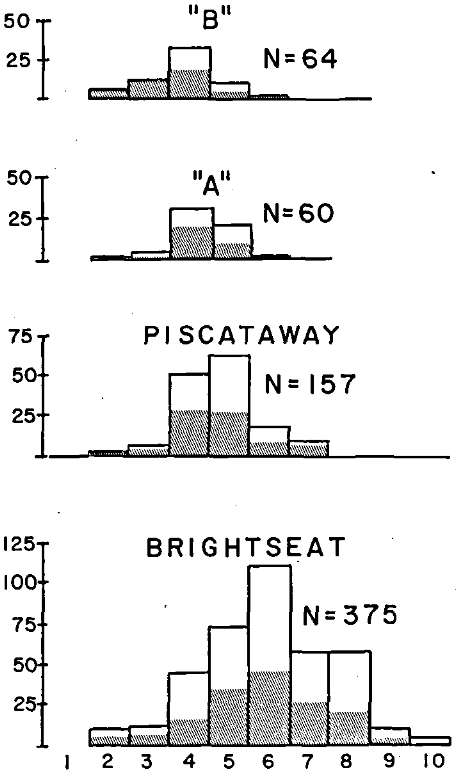


Fig. 5. Size-frequency distributions of M. (G.) uhleri *from the Brightseat Formation and from the Piscataway Member and Members A and B of the Aquia Formation. Total height of bar indicates number of specimens for which either an exact measurement or an approximation of shell size (see text) was obtained; shaded portion of bar indicates number of complete specimens, subsequently used in principal components analysis and other biometric studies, of a particular size class. N=total number of specimens measured exactly or approximately.*

ments for it. We have thus used natural breaks in the abundance of the species as criteria for defining 'statistical populations' of *M. (G.) uhleri.*

Many of the specimens which we identified as *M. (G.) uhleri* were broken; we believe this circumstance to be much less a reflection of immediate post-mortem reworking than a consequence of cracking and splitting after the valves had been collected, exposed to the atmosphere, washed free of sediment, and subjected to several cycles of identification and counting. We adopted the convention of recording as an individual specimen only a valve which retained the entire hinge line intact. A sample whose only occurrence of *M. (G.) uhleri* was as one or more fragments of shell, with no portion of the hinge line present, was arbitrarily counted as having yielded one specimen. In all, 897 countable specimens were obtained from the 40 Brightseat and Aquia horizons where the species occurred. Of these, valves which preserved the entire anterior, posterior, or mid-ventral portion of the valve margin (670 specimens) were measured (using a binocular microscope and millimeter scale, since the specimens were too fragile for measurement with vernier calipers) for an approximation of shell size, employing the assumption that the valve is nearly circular and the umbo is centrally situated. As we shall show later, these assumptions are not entirely correct, but since the shell-size measurements made in this way were rounded to the nearest mm, the simplifying definitions of shell shape are accurate enough for a survey of size distribution in a large sample. Fig. 5 presents histograms summarizing the results of these measurements on 656 specimens from the four stratigraphically-defined 'collections'. Note that the modal size decreases progressively through time; sample sizes for each collection are given on the figure.

We then selected all those specimens (318 valves) for which the entire margin of the valve was complete, photographed these at a magnification of ×5, and on each photograph made the six measurements defined in fig. 6. The use of photographs minimized handling of our small, fragile specimens; also, such characters as AL and Angle A (fig. 6) can be measured more easily on a photograph than on an actual specimen (cf. Andrews 1974). The measurements made on the magnified specimens were converted to natural-size values before statistical calculations were undertaken; the results of statistical analysis of the measurement data are reported below.

Although some of the computational programs which we used allow for missing data, we measured only complete valves in this phase of the study, believing our sample sizes to be large enough that including measurement data from incomplete specimens would not have provided sufficient additional information to justify the laborious photographic work involved in obtaining it. This decision also enhanced the confidence which could be placed in the results of our multivariate statistical analyses, as measures of correlation among the several pairs of characters

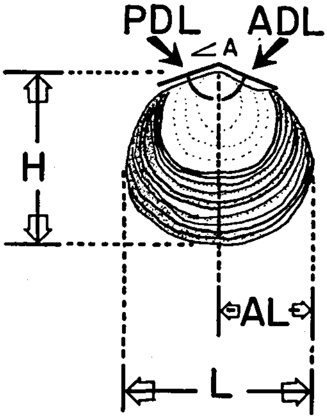


Fig. 6. Characters measured for multivariate analysis. L, shell length; H, shell height; AL, anterior length; ADL, anterior dorsal length; PDL, posterior dorsal length; A, apical angle. Note change in shell sculpture, from nearly smooth on juvenile to corrugated on adult portion of shell.

were based on the same number of comparisons in all cases. We found no evidence that differential breakage of specimens seriously affected the distribution of sizes in the sample of specimens used for statistical analysis. Specimens of *M. (G.) uhleri* seem to be about equally subject to breakage whether they are small or large. Size-frequency distributions based only the more accurately measured complete valves show virtually identical patterns to those based on a larger sample, including estimates of size of incomplete valves (fig. 5).

Criteria of maturity

In a study seeking to document evolutionary changes in size and form, it is important to establish that there is no serious discrepancy among the age structures of the populations of organisms being compared, so far as this is possible with fossil material. We assume that *M. (G.) uhleri,* like most bivalves, continued to grow throughout its life span, but that the rate of growth was notably faster for young than for older individuals (Wilbur & Owen 1964). Hall (1975) states that the annual rate of growth in young individuals of the Recent bivalve *Tivela stultorum* may be more than 20 times that in older ones. We are unable to state unequivocally that an increment in unit length on a Brightseat specimen necessarily represents the same lapse of time as a similar increment on an Aquia one. We should like eventually, once the process of formal publication and selection of type material for our larger systematics study has been completed, to section some of our specimens from the various Brightseat-Aquia horizons and paleoenvironments for growth-increment analysis (Berry & Barker 1975; Clark 1975).

There is no clearly definable terminal adult stage in lucinid bivalves, but in studying other species of this group we have noticed that an apparent criterion of maturity is a tendency for the adductor muscle scars to be distinctly impressed, even appearing somewhat sunken into the valve interior. This probably comes about because the surface of the mantle within the pallial line, exclusive of the areas of muscle insertion, begins to deposit calcium carbonate more vigorously on the inner ostracum after growth at the valve margin has slowed down (Morton & Yonge 1964). In our material, only specimens less than about 3 mm long appeared by this criterion to be immature. Judging from the distribution of sizes in fig. 5, therefore, we regard all four of our major collections as being composed almost entirely of adult individuals. But, for the reasons stated above, we can neither confirm nor deny with certainty that the differences in modal size are strictly proportional to differences in age at death.

Another possible means of distinguishing juvenile from adult specimens of *M. (G.) uhleri* was suggested by the observation that with growth the nature of the shell sculpture changes (fig. 6). In early ontogeny the shell is nearly smooth, with only fine concentric lines of growth present. Subsequently the concentric costae on the valve become more elevated, with rather deep spaces between them producing a corrugated effect. As with the deep impression of the muscle scars, we interpret the change in sculpture as a consequence of decreasing growth rate with increasing age. Although the change in sculpture is a clearly marked phenomenon if one compares the earliest and the latest portions of a single large shell, on most valves the transition between smooth and corrugated sculpture is gradual rather than abrupt. In trying to quantify this character, we found it impossible to define consistently the exact onset of the corrugated sculpture, and thus we did not use the location of the transition as a character in our quantitative study of morphological variation in *M. (G.) uhleri*.

We do, however, have results from a small-scale study of variation in the onset of sculptural change (data collected as part of a pilot study along conventional numerical taxonomic lines, before we had obtained any evidence on possible patterns of size variation). We used 40 randomly selected specimens representing the entire stratigraphic range and a broad spectrum of sizes (2.0–7.8 mm long) from the Brightseat and Aquia collections. In the specimens measured, the onset of the change in sculpture occurred at shell heights (fig. 6) of as little as 1.8 mm to as great as 5.6 mm. For the sample as a whole, the mean value for 35 valves, 2.6–7.8 mm long, was 3.2 mm; on 5 valves, ranging in length from 2.0 to 4.2 mm, the transition had not occurred. For each of the four collections, except perhaps that from Member A, the character shows considerable intrapopulation variability (CV 15.2 for Member A, 30.9–32.8 for the other samples); but individuals on which the change occurs at a shell height of 5 mm or more appear to be confined to the Brightseat. Analysis of variance indicates significant difference among the means for the four collections, but not at an outstanding level of significance ($0.05>P>0.02$). Considering the Brightseat versus the three combined Aquia samples, the mean value of the height at transition in sculpture is 4.2 mm for the former and 2.9 mm for the latter (corresponding approximately to the criterion of maturity based on strength of muscle-scar impression). Specimens on which the change occurs at a height as small as 2 mm, however, occur throughout the section. The possible significance of an apparent decrease in size at maturation will be discussed in more detail below.

Results of morphometric analysis

Size variation

The collections from the lower parts of the Brightseat-Aquia section are characterized by a grater proportion of large individuals of *M. (G.) uhleri* than are those from the upper ones. Modal size is 6 mm for the Brightseat collection, 5 mm for that from the Piscataway Member, and 4 mm for both the Member A and Member B ones. Furthermore, although in the Brightseat a substantial proportion (20%) of the specimens are 7 mm in length or more, individuals of this size are quite rare in the other three collections (fig. 5). We doubt that the distribution of observed sizes has been seriously affected by bias due to the breakage of specimens.

We also consider preservational bias favoring small individuals in the stratigraphically higher samples (e. g., diagenetic effects, or differential size-sorting by syndepositional sedimentary processes) unlikely to account for the observed size differences. In all four collections, specimens of *Myrtea* occur with individuals of other bivalve species which may be up to 5 or 10 times larger than the lucinid. In the upper part of the Aquia, specimens of *Corbula* spp., common associates of *M. (G.) uhleri*, fall most frequently into a size range of 5–9 mm, closely corresponding to that portion of the total *Myrtea* size range which is apparently truncated in these upper horizons. Numerous juvenile individuals of a variety of characteristically large-sized (40–100+ mm in adult length) bivalve species, also falling into this approximate size range, are likewise found in our upper Aquia collections. We imply no necessary interaction among these species, but simply use these data to point out the unlikelihood that the relative rarity of large *Myrtea* specimens in the upper horizons results from a preservational bias operating only on lucinids.

Table 2 summarizes the basic univariate statistics for measurements of each of the characters defined in fig. 6 for the samples of complete specimens from the four horizons. To test for the statistical 'reality' of the apparent unidirectional decrease in shell size, we used an approximate *t*-test for samples whose variances are not assumed to be equal (Sokal & Rohlf 1969: 374–376) to compare mean lengths. By this test, the differences between means for stratigraphically adjacent Aquia samples are just on the borderline of statistical significance ($0.05>P>0.01$ for the Piscataway-Member A comparison, and $0.01>P>0.001$ for Member A vs. Member B). Differences between all other pairs of mean lengths are highly significant ($P\ll0.001$). We turn to a consideration of a technique which assists us in determining the relationship between length, here regarded as an estimator of overall shell size, and the other characters. Data on the

Table 2. Means and standard deviations for L, H, AL, ADL, PDL, AND <A for each of the four collections of *Myrtea (Gonimyrtea) uhleri*.

		L (mm)		H(mm)		AL(mm)		ADL(mm)		PDL(mm)		<A(°)	
	N	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Brightseat	156	5.84	1.49	5.44	1.43	2.80	0.74	2.10	0.55	2.86	0.73	130.2	5.06
Piscataway	79	4.74	1.18	4.52	1.18	2.26	0.57	1.78	0.49	2.50	0.62	123.1	5.15
Member A	31	4.30	0.67	4.04	0.66	1.98	0.36	1.64	0.31	2.26	0.40	122.4	6.15
Member B	43	3.74	1.05	3.50	0.98	1.79	0.50	1.50	0.35	2.06	0.58	120.6	5.85

measurements of all these characters are summarized in table 2.

Principal components analysis

This multivariate statistical technique permits simultaneous consideration of variation in all the characters measured, and allows us to distinguish the effects of overall change in size with growth from those components of variability which are relatively independent of size (Blackith & Reyment 1971; Sneath & Sokal 1973). In our study we used the principal components analysis (PCA) program of the NTSYS (Numerical Taxonomy System) package of biometric and numerical taxonomic programs written by F. J. Rohlf, J. Kishpaugh, and D. Kirk of SUNY at Stony Brook.

We carried out PCA on the specimens from each of the four stratigraphically-defined collections of *M. (G.) uhleri* (N = 156, 79, 31, and 43, in ascending stratigraphic order), and on the total collection of complete specimens from the Brightseat and Aquia (N = 318). (The total collection included an additional 9 specimens, 5 from Member D and 4 from Member E of the Aquia; sample size was inadequate to justify performing separate statistical analyses on these two groups of specimens.) Results of the PCA on the total sample are summarized in table 3; with a few minor exceptions to be mentioned subsequently, the patterns of variation in the five PCA's corresponded quite closely. The correlation matrix whose eigenvalues were extracted was calculated from the original measurements of the various characters, with angular values transformed to radians to bring the magnitude of these measurements into closer consonance with that of the dimensional ones. We also performed PCA's using logarithmically transformed data, but the only effect of this transformation was to increase modestly the percentage of variation explained by the first principal component axis.

For each of the five analyses, about 70–80% of the variation in the correlation matrices is explained by the first principal component, with which the five dimensional measures (L, H, AL, ADL, and PDL) are strongly associated (table 3). This principal component axis is readily interpreted as representing the influence of overall increase in size–a specimen 8 mm long will tend to be about twice as high as one which is 4 mm long, and the other dimensions will also be proportionately increased. The first axis explains 81% of the variability for the Brightseat sample, 78% for the Piscataway, 70% for Member A, and 84% for Member B.

Table 3. Results of principal components analysis of measurements on 318 Brightseat and Aquia specimens of *Myrtea (Gonimyrtea) uhleri*.

	Matrix of correlations Character						Character	Eigenvalues and Eigenvectors Axis and (Percent of variability explained)			
	L	H	AL	ADL	PDL	<A		1(83.2)	2(12.9)	3(1.9)	4(1.4)
L	1.000						L	0.993	0.032	0.060	–0.027
H	0.989	1.000					H	0.986	0.104	0.057	–0.051
AL	0.966	0.966	1.000				AL	0.974	0.031	–0.025	–0.206
ADL	0.922	0.926	0.909	1.000			ADL	0.944	0.146	–0.274	0.109
PDL	0.955	0.955	0.903	0.894	1.000		PDL	0.955	0.154	0.178	0.165
<A	0.499	0.435	0.485	0.384	0.382	1.000	<A	0.532	–0.846	–0.006	0.034

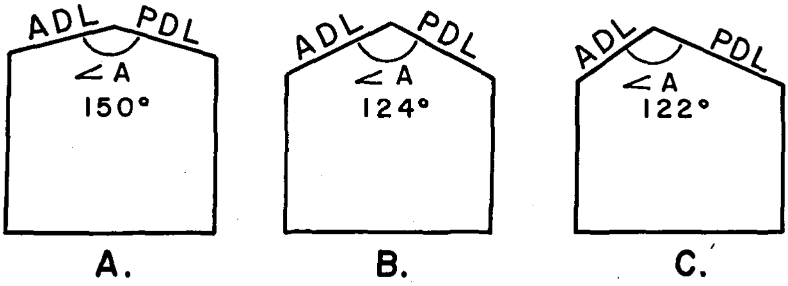


Fig. 7. Stylized representations of M. (G.) uhleri *indicating manner in which magnitudes of measurements of dorsal length vary with change in apical angularity and with shift in position of the umbo (see text). Abbreviations as in fig. 6.*

About 15% of the total variability in each of the collections is explained by the second principal component, which is associated predominantly with the apical angle measurement. In all cases the correlation between Angle A and the dimensional values is substantially lower than the correlations among these latter characters, although there is only one sample (Piscataway Member) in which the correlation of Angle A with length, etc., is not significantly different from zero. A good deal of the variability in the apical angle measurement is thus apparently independent of the size of the shell. To the second axis there is also generally a modest contribution, opposite in sign from that of Angle A, of ADL and/or PDL. These measurements, two legs of the triangle of which Angle A is the apex, are relatively longer on more trigonal (lower Angle A) than on more quadrate (higher Angle A) specimens of a given size. Since, when size is held constant and angularity varied, these two measurements will tend to decrease as Angle A increases, and vice versa, their association with angularity on Axis 2 is marked by an opposition between their sign and that of Angle A.

The third and fourth principal components together take up only 5% or less of the total variability (except in the sample from Member A, where they jointly account for 13%), but they illustrate some interesting minor features of variation. Axis 1 has presumably removed the effect of overall size and Axis 2 that of variation in angularity independent of size. If both size and angularity are held constant and only the location of the umbo is changed, ADL will be shorter and PDL longer on specimens where the umbo is nearer the anterior end of the shell, and vice versa (figs. 7B, C). The negative association of these two characters on the third principal component axis presumably reflects this aspect of shape variability. The magnitude of a given measurement of ADL or PDL is thus influenced by three factors: the size of the shell (most importantly), the trigonality or quadrateness of the shell, and the location of the beaks.

Axis 4, indicating a negative association between anterior length (AL) and the measures of dorsal length, may be affected by the presence of some specimens in which the valve is trigonal (high ADL and PDL) and the beaks are placed rather far forward (low AL). Such specimens occur in all four collections but are most abundant in that from Member A. In that sample the fourth axis represents 6% of total variability; in the others it accounts for 2% or less.

Variation in individual characters

Having determined that the broad patterns of relationship among morphological characters are constant throughout the history of *M. (G.) uhleri* in the Potomac Valley Paleocene, we turn to an examination of the pattern of change in individual characters. A linear trend toward decrease in mean size (table 1) is associated with a smaller mean size of the apical angle (a more trigonal shell) in the three Aquia samples than in the Brightseat sample. This association is, of course, predictable from the weak, but for the species as a whole still significant, correlation between angularity and size. In lucinacean bivalves, the ligament area (posterior to the beaks) is small and narrow in young individuals, but tends to broaden as the shell grows, thus elevating the posterior dorsal termination of the valve nearer to the level of the umbo. In larger specimens of *M. (G.) uhleri,* also, the anterior dorsal termination of the valve develops a slight upward flare, apparently associated with the dorsal broadening of the anterior adductor impression. This similarly brings the anterodorsal margin upward. Both these effects tend to make large shells more quadrate. Since the stratigraphically higher collections have fewer large individuals, we expect them to be on average more trigonal.

The correlation between size and angularity is real, but imperfect. The original measurements of our six characters show that specimens 2 to 3 mm long (possibly still immature) never have an apical angle measurement greater than about 125°. Only the largest specimens (7 mm in length or more, occuring almost exclusively in the Brightseat) attain the maximum observed angular values of about 140°. But specimens ranging in size from 2 mm to 9 mm long may all have angularity values in the vicinity of 110°–125°. There is thus a certain asymmetry in the relationship of size to angularity, in that small specimens cannot be quadrate, only trigonal; but large ones may be either trigonal or quadrate. This relationship holds for all four collections. In that from the Piscataway Member, the correlation between size and angularity is nonsignificant because this sample lacks any highly quadrate large specimens to balance the several notably trigonal small ones.

We thus observe (table 2) a change from an early population spanning a broad range of sizes, with the smallest specimens being trigonal and the largest ones tending to be more quadrate, to later populations in which the size spread has been diminished by a virtual truncation of the large-size end of the range. Not only do the later populations have a smaller mean for Angle A, but the range of values for angularity shows a modest downward shift (116°–141° for the Brightseat; 112°–134° for the Piscataway; 108°–137° for Member A; and 108°–135° for Member B).

The relationships between angularity and the measures of dorsal length brought out by the principal component analysis (table 3; fig. 7) permit us to interpret the pattern of change in ratios between pairs of dimensions, taking the largest dimension, length, as an estimator of overall size. Associated with the decrease in apical angularity are increases in the mean ratios of anterior dorsal length and posterior dorsal length to total length (table 4; fig. 8B). This pattern of change is predictable from the geometric relationship between angularity and dorsal lengths demonstrated earlier, such that more trigonal shells, which usually are also smaller shells, have relatively greater dorsal lengths. The other two size ratios, height/length and anterior length/length, show no discernible trends (table 4; fig. 8A), and, in fact, scarcely differ among the four collections, except that height/length has a slightly but significantly lower mean value for the Brightseat than for the three Aquia collections.

Interpretation of the observed pattern of change

The most evident feature of the Paleocene record of *Myrtea (Gonimyrtea) uhleri,* as recorded by the characters chosen for this study, is the progressive diminution in modal and mean size (table 2; fig. 5). Associated with this change in size through time are changes in shape which, for anyone population, correspond to a small component of ontogenetic change in form. If it is conceded that we can largely eliminate substantial sampling bias as accounting for the differences in mean size, we suggest three possible environmental explanations for the observed correspondance between decreasing mean size and progressive shallowing of the Paleocene sea (fig. 4). On the basis of the available evidence, we are not able to determine which of these is most likely; and, indeed, more than one may have been operating. The postulated explanations are as follows:

(1) No difference in potential mean longevity of *M. (G.) uhleri* populations from the lower and the upper horizons, but a difference in rates of growth in more offshore and more nearshore environments, and thus in the average size of individuals of a particular age. Clark (1975: 103) has found that "individuals living in variable environments, such as shallow water, are subject to disturbances which can limit or preclude

Table 4. Means and standard deviations for the ratios H/L, AL/L, ADL/L, and PDL/L for each of the four collections of *Myrtea (Gonimyrtea) uhleri.*

		H/L		AL/L		ADL/L		PDL/L	
	N	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Brightseat	156	0.928	0.037	0.479	0.035	0.360	0.041	0.490	0.039
Piscataway	79	0.950	0.047	0.475	0.042	0.373	0.041	0.531	0.042
Member A	31	0.941	0.043	0.456	0.050	0.382	0.049	0.525	0.057
Member B	43	0.938	0.055	0.480	0.035	0.411	0.051	0.551	0.033

growth for periods of days or weeks, resulting in gaps in the growth [increment] record". He does not address the question of whether the interruptions in growth found to be more frequent in shallow-water environments substantially affect ultimate size in bivalves, but his findings do suggest a possible mechanism whereby growth rate might have been lessened in the higher-energy upper Aquia facies.

(2) Decrease in mean achieved longevity, resulting from an increasing incidence of (a) episodic sedimentation, with burial beneath thicknesses of sediment exceeding the maximum burrowing depth, or (b) disinterment by intermittently strong wave or current activity, with disinterred individuals, saddled with the inefficient burrowing mechanism which appears to characterize lucinids generally, being vulnerable to predation, desiccation, or starvation. The observed size decrease would then be a function of preservation of individuals which had died at progressively smaller sizes, as episodic mortality became more frequent during regression. This suggestion is not necessarily contrary to (1); in fact, both mechanisms may have acted in concert, with small-scale episodes of unfavorable environmental conditions causing temporary stoppage of growth, and large-scale ones proving fatal.

(3) Acceleration of the rate of maturation, with sexual maturity (and hence termination of the stage of rapid growth) occuring at progressively younger ages, as a result of more stringent selection for earlier maturation in environments more often subjected to intolerable conditions, as in (2). In such environments, those bivalves which could reproduce when relatively young and small would have a higher probability of living long enough to leave descendants than would those which had wait until later to reproduce. We are not able to state for certain whether our data discussed earlier, suggesting a smaller size at transition from smooth to corrugated sculpture for the Aquia specimens than for those from the Brightseat, do reflect such a paedomorphic effect ('progenesis' of Gould 1976), or simply indicate an over-all slowdown in rate of growth.

In addition to our comparisons of mean size among stratigraphically successive samples, we have further compared mean lengths for those specimens occuring in the more nearshore Facies 2 and the more offshore Facies 3, without regard to stratigraphic position. (There are only 15 complete specimens from Facies 4; sample size is thus too small to merit including a Facies 4 comparison.) Observed mean length is 5.38 mm for Facies 3 specimens ($N = 199$), and 4.45 mm for those from Facies 2 ($N = 104$). By the approximate t-test appropriate when variances are not assumed to be equal, the difference between these means is highly significant ($P \ll 0.001$). Specimens from shallow subtidal environments thus average nearly 20% smaller than those from farther offshore. This evidence further strengthens our inference that size decrease (however achieved) was an adaptation to more rigorous environmental conditions recorded by the nearshore facies.

Many paleontological studies which have documented ecologically associated variation in form have sought some immediate selective advantage for the form changes themselves (e. g., increased burrowing efficiency in infaunal bivalves, greater mechanical stability in epifaunal bivalves and brachiopods). For *M. (G.) uhleri*, it is possible to postulate that smaller and hence more trigonal individuals may have been somewhat more efficient burrowers than larger and hence more quadrate ones, and thus have been more readily able to reorient themselves in

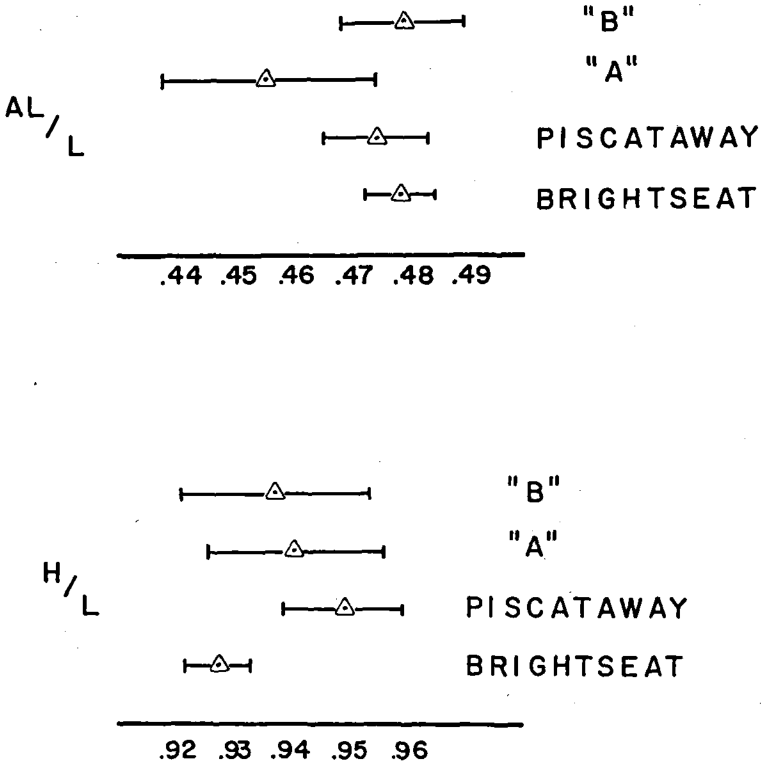
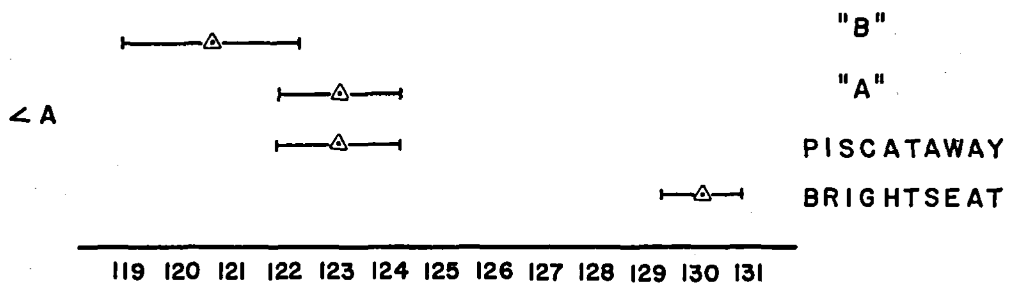


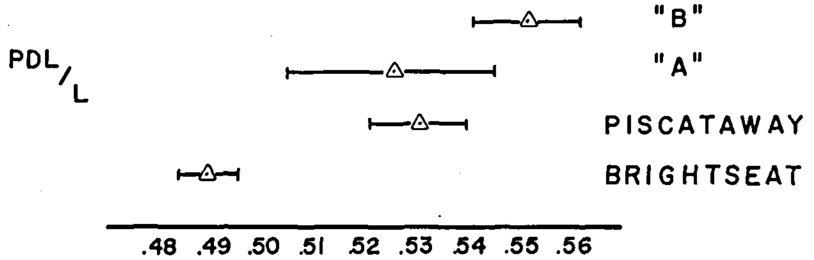
Fig. 8. Means (dots enclosed in triangles) and 95% confidence intervals (bars) plotted against stratigraphic position for four shape ratios and for apical angle (degrees). Abbreviations as in fig. 6. Fig. 8A: characters showing little or no change through time. Fig. 8B (p. 173): characters showing progressive change through time.

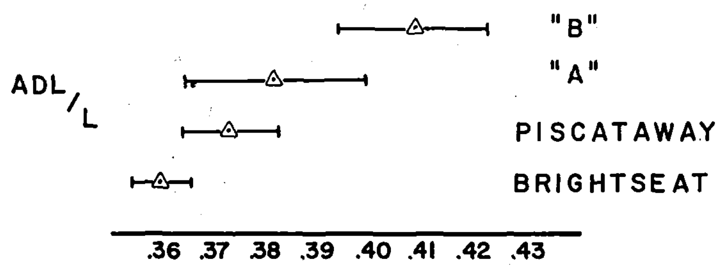
the sediment after the passage of storms. Such a macromorphological explanation, while plausible, appears not to be required here, for the very similar results of principal components analysis on the four individual collections indicate that the pattern of ontogenetic change in shape (essentially only change in apical angularity) did not change through time. Necessarily, therefore, samples composed on average of smaller individuals – whether the diminution in mean size resulted from slower growth rates, mortality at younger ages, selection for earlier maturation, or simply the inevitable vagaries of sampling error (which last proposition we believe can be largely discounted for our material) – also differ in the mean values of those characters describing angularity. We have no evidence of decreasing apical angularity through time for individuals of constant size.

Conclusions

In earlier presentation of some of these results, one of us (Bretsky 1974) had interpreted the apparent undirectional change in mean size of *M. (G.) uhleri* as a possible case of 'phyletic gradualism' (Eldredge & Gould 1972; Gould & Eldredge 1977). With a more refined understanding both of Brightseat-Aquia paleoenvironments and of the rigor of arguments necessary to document that morphological change is actually gradual, we now advocate a somewhat different interpretation of the data. The accuracy with







which individual beds at different localities in the Potomac River Valley Paleocene can be correlated is, unfortunately, not high enough to permit us to duplicate the fine subdivisions of evolving lineages presented by Kellogg (1975) and Gingerich (1976). Our study, like these two (as noted by Gould & Eldredge 1977) also lacks sufficiently broad geographic coverage, with adequate stratigraphic control, to permit a frame-by-frame reconstruction of evolutionary events throughout the entire distributional range of *M. (G.) uhleri.*

With, in effect, only four distinct stratigraphic levels of adequate sample size, we cannot persuasively argue for a constant unidirectional trend toward size decrease in *M. (G.) uhleri.* We believe, however, that the level of documentation does suffice to indicate an association between greater environmental rigor and smaller size. We hope that the presentation of these data will encourage other workers to look for similar relationships in relatively eurytopic species. If such findings can be duplicated elsewhere, perhaps observations can be made which might permit choice among the three possible population-level explanations for size decrease outlined above.

Acknowledgments. Financial support for this investigation came from the Smithsonian Research Foundation and from the National Science Foundation (Grant GB-27441). The State University of New York at Stony Brook also furnished computer time. Robert Beauchamp and Thor Hansen, while students at George Washington University, collected and prepared many of the specimens of *Myrtea (Gonimyrtea) uhleri*. We thank John Kishpaugh and Elaine Brown for assistance with the use of computer programs, and John Sulima, Doreen Fundiller, Pauline Mohr, and Gayle Lohmann for the many hours they spent in photographing specimens. Martin A. Buzas, Stephen Jay Gould, and Claus Heinberg read various incarnations of the manuscript, and we appreciate their constructive commentary.

Dansk sammendrag

Fire stratigrafisk adskilte populationer af den lucinide musling Myrtea (Gonimyrtea) uhleri er analyseret med henblik på morfologisk variation. Analysen viser et tydeligt fald i gennemsnitlig størrelse op gennem lagserien. Da lagserien repræsenterer et regressivt forløb betyder det, at de kystnære former er mindre end dem fra dybere vand. Forskellen beløber sig til næsten 20%. Faldet i gennemsnitlig størrelse menes fremkommet ved en række miljømæssige påvirkninger, dog diskuteres også muligheden for, at der kunne være tale om en egentlig fyletisk udvikling mod mindre gennemsnitlig størrelse.

References

Allen, J. A. 1958: On the basic form and adaptations to habitat in the Lucinacea (Eulamellibranchia). *Phil. Trans. roy. Soc. London* B 241: 421–484.

Andrews, H. E. 1974: Morphometrics and functional morphology of *Turritella mortoni*. *J. Paleont.* 48: 1126–1140.

Beauchamp, R. G. 1969: *Stratigraphy and depositional environments of Paleocene sediments in the lower Potomac River Valley.* Unpubl. M. S. Thesis, George Washington University, 109 pp.

Berggren, W. A. 1965: Some problems of Paleocene-Lower Eocene planktonic foraminiferal correlations. *Micropaleontology* 11: 278–300.

Berry, W. B. N. & Barker, R. M. 1975: Growth increments in fossil and modern bivalves. *In* Rosenberg, G. D. & Runcorn, S. K. (eds.), *Growth Rhythms and the History of the Earth's Rotation,* 9–25. New York: Wiley-Interscience.

Blackith, R. E. & Reyment, R. A. 1971: *Multivariate Morphometrics.* 412 pp. New York: Academic Press.

Bretsky, S. S. 1974: A possible case of phyletic gradualism in Paleocene Bivalvia (Mollusca). *Geol. Soc. Amer. Abstracts with Programs* 6: 666.

Bretsky, S. S. 1976: Evolution and classification of the Lucinidae (Mollusca; Bivalvia). *Palaeontogr. Amer.* 50: 217–337.

Clark, G. R., II 1975: Periodic growth and biological rhythms in experimentally grown bivalves. *In* Rosenberg, G. D. & Runcorn, S. K. (eds.), *Growth Rhythms and the History of the Earth's Rotation,* 103–117. New York: Wiley Interscience.

Clark, W. B. 1895: Contributions to the Eocene fauna of the Middle Atlantic Slope. *Johns Hopkins University Circular* 125: 3–6.

Eldredge, N. & Gould, S. J. 1972: Punctuated equilibria: an alternative to phyletic gradualism. *In* Schopf, T. J. M. (ed.), *Models in Paleobiology,* 82–115. San Francisco: Freeman, Cooper.

Gingerich, P. D. 1976: Paleontology and phylogeny: patterns of evolution at the species level in early Tertiary mammals. *Am. J. Sci.* 276: 1–28.

Gould, S. J. 1976: Palaeontology plus ecology as palaeoecology. *In* May, R. M. (ed.), *Theoretical Ecology: Principles and Applications,* 218–236. Philadelphia: Saunders.

Gould, S. J. & Eldredge, N. 1977: Punctuated equilibria: the tempo and mode of evolution reconsidered. *Paleobiol.* 3: 115–151.

Hall, C. A., Jr. 1975: Latitudinal variation in shell growth patterns of bivalve molluscs: implications and problems. *In* Rosenberg, G. D. & Runcorn, S. K. (eds.), *Growth Rhythms and the History of the Earth's Rotation,* 163–175. New York: Wiley-Interscience.

Hazel, J. E. 1968: Ostracodes from the Brightseat Formation (Danian) of Maryland. *J. Paleont.* 42: 100–142.

Hazel, J. E. 1969: Faunal evidence for an unconformity between the Paleocene Brightseat and Aquia Formations (Maryland and Virginia). *U. S. geol. Surv. Prof. Papers* 650-C, 58–65.

Jackson, J. B. C. 1973: The ecology of molluscs of *Thalassia* communities, Jamaica, West Indies. I. Distribution, environmental physiology, and ecology of common shallow-water species. *Bull. marine Sci.* 23: 313–350.

Kauffman, E. G. & Beauchamp, R. G. 1969: Sediments and faunas of Paleocene marine cycles, Potomac River Valley. *Geol. Soc. Amer. Abstracts with Programs for 1969,* (7) 119–120.

Kellogg, D. E. 1975: The role of phyletic change in the evolution of *Pseudocubus vema* (Radolaria). *Paleobiol.* 1: 359–370.

Morton, J. E. & Yonge, C. M. 1964: Classification and structure of the Mollusca. *In* Wilbur, K. M. & Yonge, C. M. (eds.), *Physiology of Mollusca* 1: 1–58. New York: Academic Press.

Rhoads, D. C. 1974: Organism-sediment relations on the muddy sea floor. *Annual Reviews of Oceanography and Marine Biology* 12: 263–300.

Sneath, P. H. A. & Sokal, R. R. 1973: *Numerical Taxonomy.* 573 pp. San Francisco: Freeman.

Sokal, R. R. & Rohlf, F. J. 1969: *Biometry.* 776 pp. San Francisco: Freeman.

Stanley, S. M. 1970: Relation of shell form to life habits of the Bivalvia (Mollusca). *Mem. geol. Soc. Amer.* 125: 296 pp.

Wilbur, K. M. & Owen, G. 1974: Growth. *In* Wilbur, K. M. & Yonge, C. M. (eds.), *Physiology of Mollusca,* 1. New York: Academic Press.

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

ARNE ROSENKRANDS LARSEN & NIELS OLUF JØRGENSEN

Larsen, A. R. & Jørgensen, N. O.: Palaeobathymetry of the lower Selandian of Denmark on the basis of foraminifera. *Bull. geol. Soc. Denmark,* vol. 26, pp. 175–184. Copenhagen, December 1st 1977.

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.

Arne Rosenkrands Larsen & Niels Oluf Jørgensen, Institute of Historical Geology and Palaeontology, Øster Voldgade 10, 1350 Copenhagen K, Denmark, August 1st, 1977.

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

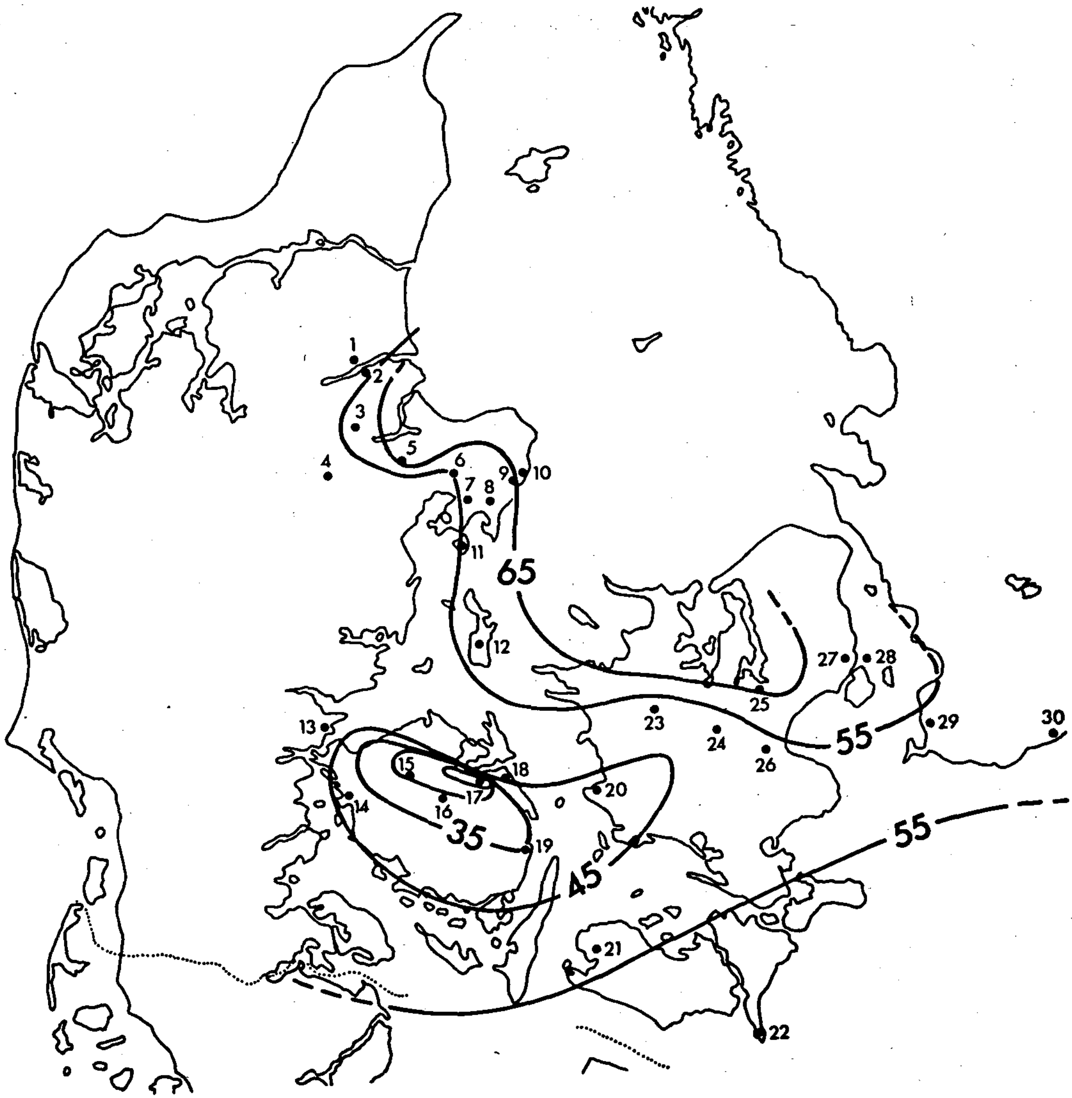


Fig. 1. Map indicating position of localities (marked by numbers) and iso-departurelines reflecting the bathymetry of the Selandian sea.

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.*

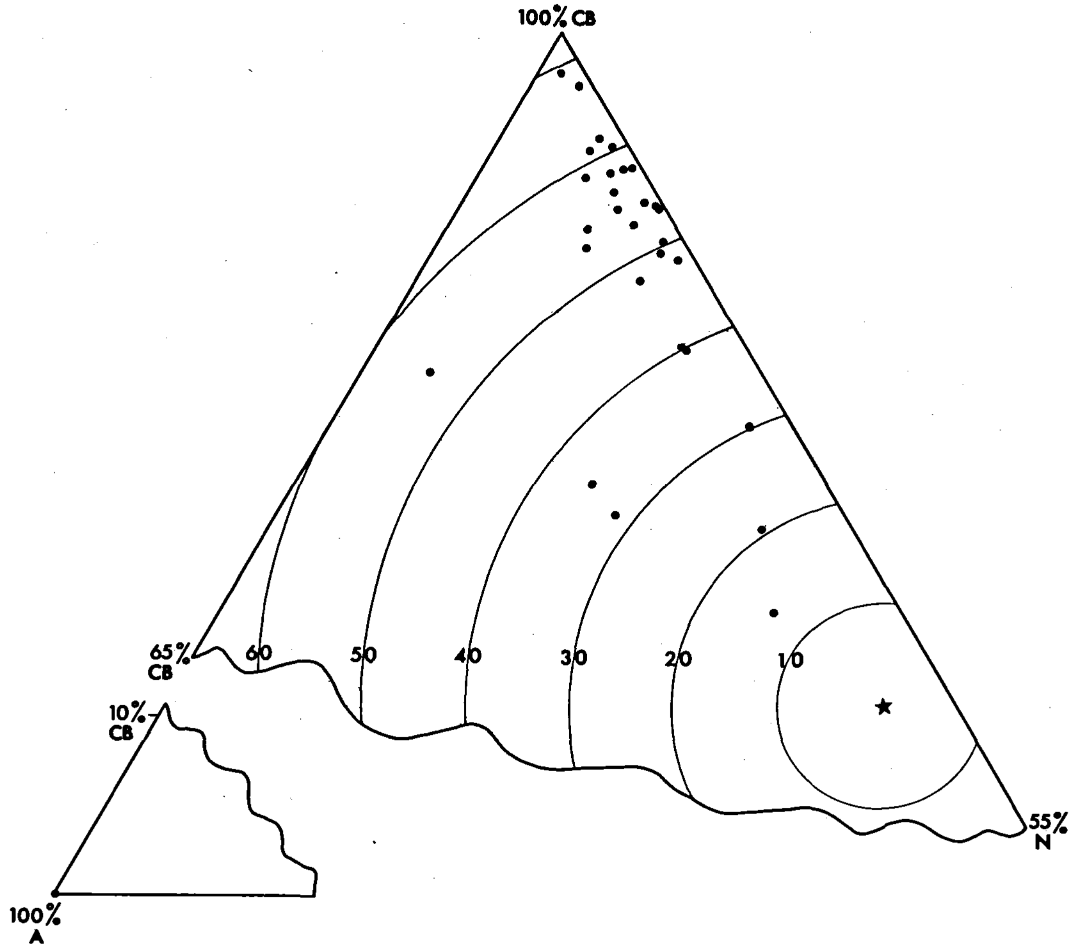


Fig. 2. Triangular graph from which departure units can be obtained. •: composition of foraminiferal fauna in the target environment (5, Hvalløse conglomerate). Composition of assemblages used in the reconstruction of the Selandian structure (fig. 1). CB: calcareous benthic foraminifera excluding Nodosariacea,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

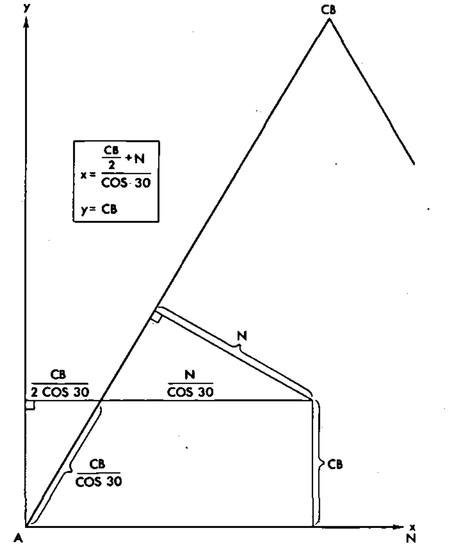


Fig. 3. Triangular graph showing how a point in the triangular graph is transferred to a x/y coordinate system. CB, A and N as in fig. 2.

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

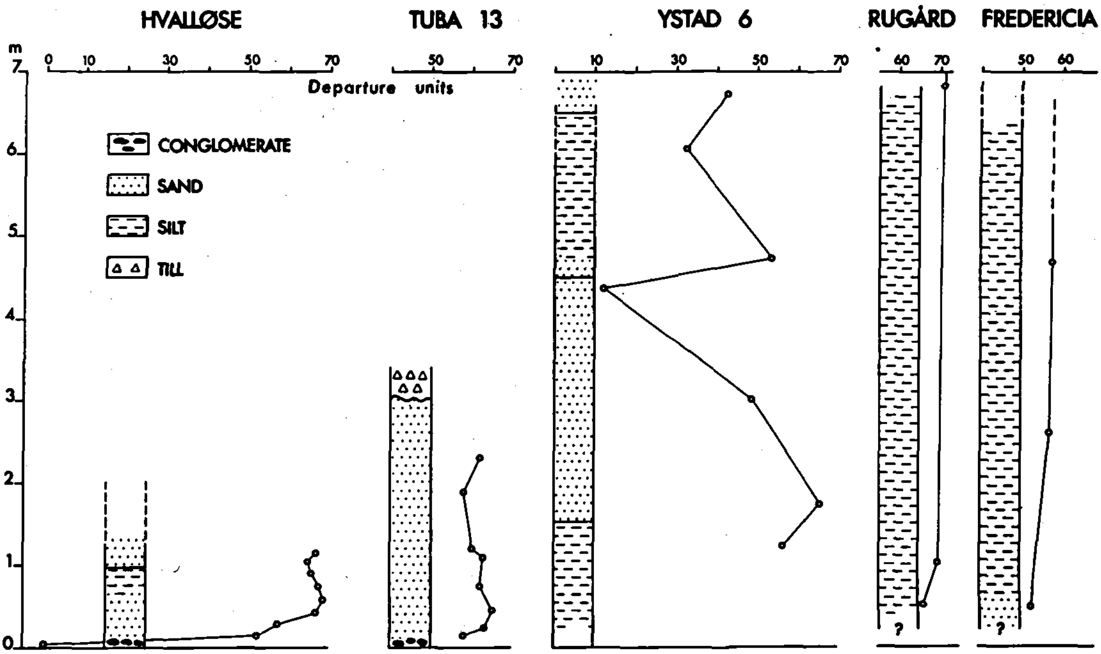


Fig. 4. Lithology and departure units in different levels of the sequences examined. Vertical axis: level above Danian. Horizontal axis: departure units indicated by the composition of the foraminiferal fauna.

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.

Acknowledgements. H. Egelund prepared the drawings and R. Bromley improved the English text. Samples have kindly been placed at the authors' disposal by Inger Bang (Geological Survey of Denmark) and B. B. Andersen, (Geological Survey of Greenland). The Laboratory of Micropalaeontology, University of Aarhus and the Geological Museum, Copenhagen kindly gave access to their collections of well material.

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.

References

Andersen, H. L. & Tychsen, J. 1976: Danien-kalkens overfladetopografi i egnen omkring Århus. *Dansk geol. Foren., Årsskrift for 1976,* 69–73.

Bandy, O. L. 1956: Ecology of foraminifera in northeastern Gulf of Mexico. *U.S. geol. Survey prof. Paper* 274 G: 179–203.

Berggren, W. A. 1972: A Cenozoic time-scale – some implications for regional geology and paleobiogeography. *Lethaia* 5: 195–215.

Berggren, W. A. & Aubert, J. 1975: Paleocene benthonic foraminiferal biostratigraphy, paleobiogeography and paleoecology of Atlantic-Tethyan regions: Midway-type fauna. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 18: 73–192.

Berthelsen, O. 1962: Cheilostome bryozoa in the Danian depostis of East Denmark. *Danmarks geol. Unders.* (2) 83: 290 pp.

Brodniewicz, I. 1965: Recent and some Holocene foraminifera of the southern Baltic Sea. *Acta Palaeontologica Polonica* 10(2): 131–248.

Brotzen, F. 1948: The Swedish Paleocene and its foraminiferal fauna. *Sveriges geol. Unders.* (C) 42: 1–140.

Buzas, M. A. & Gibson, T. G. 1969: Species diversity: benthonic Foraminifera in western North Atlantic. *Science* 163: 72–75.

Dinesen, A., Michelsen, O. & Lieberkind, K. 1977: A survey of the Paleocene and Eocene deposits of Jylland and Fyn. *Danmarks geol. Unders.* (B) 1: 15 pp.

Franke, A. 1927: Die Foraminiferen und Ostracoden des Paläozäns von Rugaard in Jütland und Sundkrogen bei Kopenhagen. *Danmarks geol. Unders.* (2) 46: 49 pp.

Gibson, T. G. & Buzas, M. A. 1973: Species diversity: Patterns in Modern and Miocene Foraminifera of the eastern margin of North America. *Bull. geol. Soc. Amer.* 84: 217–238.

Gry, H. 1935: Petrology of the Paleocene Rocks of Denmark. *Danmarks geol. Unders.* (2) 61: 171 pp.

Hansen, H. J. 1968: On the biostratigraphical age of the lower Selandian of Denmark. *Meddr dansk geol. Foren.* 18: 277–284.

Hansen, H. J. 1970: Danian foraminifera from Nûgssuaq, West Greenland. *Meddr Grønland* 193 (2): 132 pp.

Hansen, H. J. and Andersen, B. B. 1969: The occurrence of clinoptilolite-replaced foraminifera in the Danish Upper Selandian non-calcareous greensand. *Meddr dansk geol. Foren.* 19: 197–203.

Hofker, J. 1966: Maestrichtian, Danian and Paleocene foraminifera. *Paleontographica Suppl.* 10: 1–376.

Kaesler, R. C. 1966: Quantitative re-evaluation of ecology and distribution of Recent Foraminifera and Ostracoda of Todos Santos Bay, Baja California, Mexico. *Univ.Kans. Paleontol. Contrib.* 50 pp.

Loeblich, A. R. & Tappan, H. 1964: Protista 2. *In:* Moore, R. C. (ed.): *Treatise on Invertebrate Paleontology,* C: 900 pp., New York.

Murray, J. W. 1968: Living foraminifers of lagoons and estuaries. *Micropaleonotology* 14(4): 435–455.

Murray, J. W. 1973: *Distribution and ecology of living benthic foraminiferids.* Heinemann Educational Books, 274 pp.

Murray, J. W. 1976: A method of determining proximity of marginal seas to an ocean. *Mar. Geol.* 22: 103–119.

Pegrum, R. M., Rees, G. and Naylor, D. 1975: *Geology of the north-west European continental shelf volume 2: The North Sea.* 225 pp. London: Trotman Dudley.

Phleger, F. B. 1960: *Ecology and distribution of Recent Foraminifera.* 297 pp. Baltimore: J. Hopkins Press.

Rosenkrantz, A. 1924: De københavnske grønsandslag og deres placering i den danske lagrække. *Meddr dansk geol. Foren.* 6 (23): 39 pp.

Spjeldnæs, N. 1975: Paleobiogeography and facies distribution in the Tertiary of Denmark and surrounding areas. *Norges geol. Unders.* 316: 289–311.

Troelsen, J. C. 1954: Studies on Ceratobuliminidae. *Meddr dansk geol. Foren.* 12: 448–472.

Ujiíe, H. and Kusukawa, T. 1969: Analysis of foraminiferal assemblages from Miyako and Yamada Bays, northeastern Japan. *Bull. nat. Sci. Mus. Tokyo* 12: 735–772.

Upshaw, C. F. & Stehli, F. G. 1962: Quantitative biofacies mapping. *Bull. Am. Ass. Petrol. Geol.* 46(5): 694–699.

Walton, W. R. 1955: Ecology of living benthonic foraminifera, Todos Santos Bay, Baja California. *J. Paleontol.* 29: 952–1018.

Walton, W. R. 1964: Recent foraminiferal ecology and paleoecology. *In:* Imbrie, J. & Newell, D. (edit.): *Approaches to Paleoecology,* 151–237. New York: Wiley.

Ziegler, P. A. 1975: North Sea basin history in the tectonic framework of north-western Europe. *In:* Woodland (ed.): *Petroleum and continental shelf of north-west Europe. 1: Geology,* 131–149. Barking: Applied Science Publ.

Oxygen isotope fractionation and algal symbiosis in benthic foraminifera from the Gulf of Elat, Israel

BJØRN BUCHARDT AND HANS JØRGEN HANSEN

Buchardt, B. & Hansen, H. J.: Oxygen isotope fractionation and algal symbiosis in benthic foraminifera from the Gulf of Elat, Israel. *Bull. geol. Soc. Denmark*, vol. 26, pp. 185–194. Copenhagen, December 1st 1977.

In order to investigate possible isotopic fractionations due to algal symbiosis the oxygen and carbon isotope compositions of shell carbonate from symbiont-free and symbiont-bearing benthic foraminifera have been compared to that of molluscs living at the same locality. The material was collected over a depth profile in the Gulf of Elat (Aqaba), Israel, covering the interval from 4 to 125 metres. After corrections for temperature variations with depth, characteristic ^{18}O-depletions were observed in the foraminiferal shell carbonate when compared to the molluscs. These depletions are interpreted as 1) a constant vital effect seen in all the foraminifera studied and 2) an additional, light-dependent vital effect observed in the symbiont-bearing forms only, caused by incorporation of photosynthetic oxygen formed by the symbiotic algae. This additional vital effect emphasizes the difficulties in applying foraminifera to oxygen isotope palaeotemperature analyses. No well-defined differences in carbon isotope compositions are observed between symbiont-bearing and symbiont-free foraminifera.

B. Buchardt and H. J. Hansen, Institute of Historical Geology and Palaeontology, Øster Voldgade 10, 1350 København K, Denmark. August 1st, 1977.

In recent years shell carbonate from both benthic and planktic foraminifera has been applied for oxygen isotope palaeotemperature determinations. A basic prerequisite of this type of investigation is shell formation in isotopic equilibrium with surrounding water; deviations from this (called vital effects) lead to erroneous temperature results. As has been demonstrated by several authors (Duplessy et al. 1970; Vinot-Bertouille & Duplessy 1973; Shackleton et al. 1973 and Grazzini 1976) neither benthic nor planktic foraminifera necessarily fulfil this condition, a fact that imposes serious problems on the validity of foraminiferal oxygen isotope palaeotemperatures.

It is generally accepted that several species of benthic foraminifera exhibit symbiotic relationships with algae (Boltovsky 1963; Röttger 1972 and Hansen 1975), a relationship that probably leads to enhanced growth. From studies of hermatypic scleractinian corals it is known that such relationships can cause depletion in both ^{18}O and ^{13}C in the skeleton carbonate as compared to calcium carbonate precipitated in isotopic equilibrium with surrounding water (Weber & Woodhead 1970). This leads to the suggestion that occurrance of symbiotic algae in some groups of benthic foraminifera likewise can be related to isotopic nonequilibrium shell formation. It is the purpose of this paper to demonstrate that such a relationship does exist. It is realised that algal symbiosis cannot account for all types of foraminiferal vital effects – among other reasons because deep-sea benthic forms are known to show vital effects as well (Shackleton 1974). Nevertheless the establishment of a symbiosis/vital effect relationship is of importance as some of the planktic forms widely used in isotopic palaeotemperature studies now are supposed to carry symbiotic algae (Lee et al. 1965; Anderson & Bé 1976).

The present study reports the oxygen and carbon isotopic composition of shell carbonate formed by foraminifera with and without symbiotic algae in their cytoplasm, and by molluscs living at the same localities (fig. 1). As demonstrated by Mook & Vogel (1968) and Fritz & Poplawski (1974) molluscs normally secrete their shells at or close to isotopic equilibrium when compared to surrounding water and dissolved bicarbonate. Isotopic differences between molluscan $CaCO_3$ and other types of biogenic carbonate formed under identical conditions therefore will indicate nonequilibrium shell formation (vital effect) in the latter group.

Vital effects

In the following a brief summary will be given dealing with the types and causes of vital effects

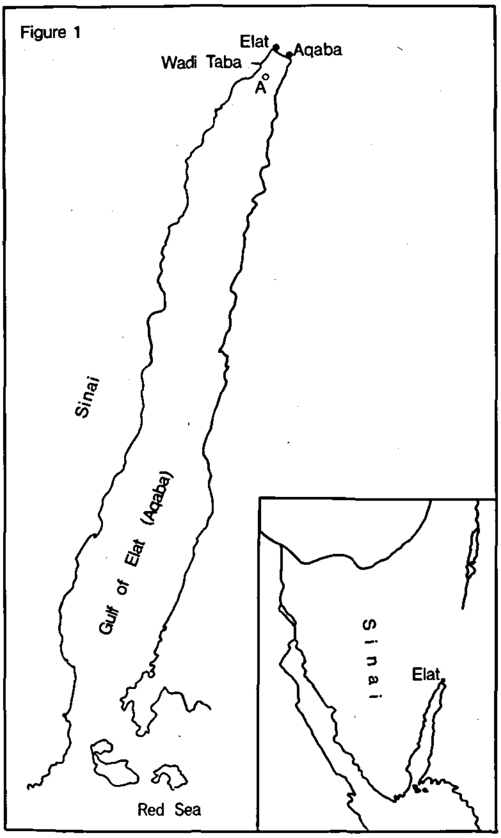


Fig. 1. Geographical location of the Gulf of Elat (Aqaba). Samples for isotopic studies were collected at Wadi Taba close to the biological station at Elat. Temperature profiles were measured at station A.

found in calcium carbonate secreting organisms. According to Lowenstam & Epstein (1954) animals secreting shell material which is not in isotopic equilibrium with the surrounding water possess a vital effect. Of the calcium carbonate secreting organisms the following groups have been demonstrated to exhibit such an effect: 1) Coelenterata (Weber & Woodhead 1970), 2) Echinodermata (Weber & Raup 1966) and 3) the Foraminifera. No information is available on bryozoans and arthropods. Besides these, vital effects are described from calcium carbonate secreting algae (Lowenstam & Epstein 1957 and Gross 1964).

Oxygen molecules in aquatic shell carbonate may have one or more of the following sources: 1) bicarbonate ions from the surrounding water which again in almost all cases are in isotopic equilibrium with oxygen in the water molecules, 2) metabolic CO_2 from the organism itself, 3) dissolved O_2 from the surrounding water and 4) oxygen produced by photosynthesis inside the organism. Of these alternatives only the first will lead to 'non-vital' shell formation, provided no biological fractionation affects the ions on their path from water to location of growth. The other oxygen sources will all cause shell formation out of isotopic equilibrium, the resulting vital effects named food effect, respiratory effect and symbiotic effect respectively. A similar classification can be applied to types of carbon atoms in the shell carbonate, although it has to be emphasized that carbon in dissolved bicarbonate ions has a highly varying isotopic composition due to its many different sources and to lack of a stabilizing reservoir.

Characteristically these effects all lead to carbonates depleted in ^{18}O and ^{13}C as compared to equilibrium conditions. Reaction products depleted in the heavy isotopes frequently are brought about by kinetic isotope-fractionation processes. Processes of this type include most of the complicated biological reactions like photosynthesis and respiration.

In foraminifera vital effects are known to exist both in benthic and planktic forms (Duplessy et al. 1970 and Shackleton et al. 1973). Algal symbiosis has been shown to play an important role in the metabolism of certain larger benthic species (Dr. Pamela Muller 1976 pers. comm.), but no proof of a symbiosis/vital effect relationship has yet been provided.

Experimental procedure

Carbon and oxygen isotope ratios were measured using the technique described by McCrea (1950). Due to analytical limitations most measurements were performed on bulk samples containing more than 30 specimens from each of the species investigated. The shell carbonate was crushed to a grain size between 150 and 75 μm, roasted in vacuo at 450°C for 30 minutes and then dissolved in concentrated phosphoric acid. Oxygen and carbon isotope ratios of the evolved

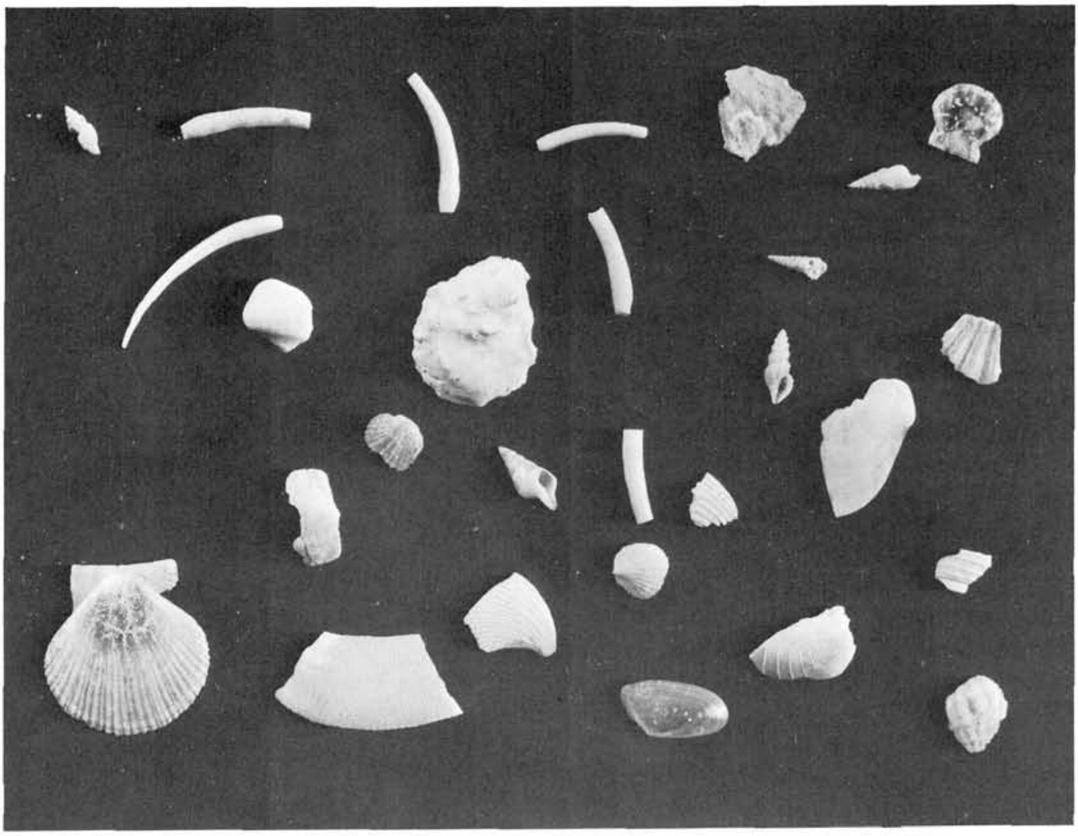


Fig. 2. Example of mollusc assemblage from which material for isotopic studies was selected. × 3.

CO_2 are expressed as permil deviations from the PDB-standard using the δ-function defined as:

$$\delta = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000\text{‰}$$

R being the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios. Reproducibility measured as standard deviation is better than ± 0.1‰ for both isotope ratios.

Material and locality

The material studied comes from the northern part of the Gulf of Elat (Aqaba), Israel and was provided as part of the joint "Micropalaeontological, Ecological and Palaeoecological Programme" in the Gulf of Elat coordinated by Z. Reiss, the Hebrew University in Jerusalem. Samples for isotopic analyses were collected from a depth profile covering the interval from 4 to 122 m by aid of a Willemoes threepoint sampler (see Hansen & Buchardt 1977). As emphasized in this study, downslope transportation of empty foraminiferal shells is very limited. This indicates that the depth distribution in the sediment shown by shells from newly dead foraminifera (shells not showing fragmentation or traces of boring activity) most likely represents the true distribution of the living species.

The same conclusion may not be valid for the larger and more resistent molluscan shells. Therefore only such shells were used where staining with the Rose Bengal method (Walton 1952) revealed remnants of soft parts and where no traces of transportation or boring activity were recognized. All molluscan shells here studied were aragonitic. Fig. 2 shows representative molluscan material, from which shells for isotopic analyses were selected.

The foraminifera used for the isotopic meas-

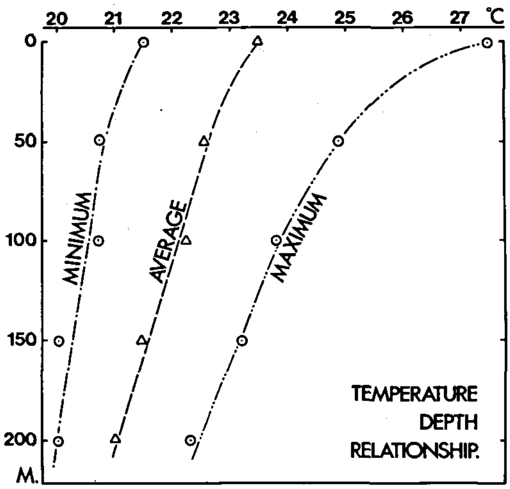


Fig. 3. Annual temperature-depth relationship at station A in the Gulf of Elat, see fig. 1. Data from Reiss et al. (1976).

urements included the following species: *Amphistegina lessonii, A. lobifera, A. bicirculata* and *A. papillosa* (see Larsen 1976), as well as *Planorbulinella* sp., *Operculina* sp. and *Heterostegina* sp., all forms containing symbiotic algae in their cytoplasm (see Hansen & Buchardt 1977). Besides these forms samples composed of the symbiont-free *Bolivina* group were analysed for comparison. All material was sampled in May.

The Gulf of Elat is a unique watermass with respect to its homogeneity in both temperature and salinity. Recent investigations, however, have revealed that small variations in both parameters do exist (Klinker et al. 1977). Fig. 3 illustrates seasonal variation and depth gradient in water temperature as measured in the northern part of the Gulf close to the Wadi Taba profile here investigated. Summer temperatures are seen to vary from 27°C at the surface to 21°C at 200 m depth. Winter temperatures are almost constant (21°C) for the entire profile.

Isotopic results

The isotopic results are presented in tables 1 and 2 and in fig. 4. In order to evaluate the isotopic differences observed the following conditions are to be considered:

1) The variability of isotopic values obtained from individual shells belonging to the same species, and the validity of the monospecific assemblage mean as employed in the present study.
2) Corrections due to seasonal variations and depth gradient in water temperature and to variations in the isotopic composition of the water.
3) Isotopic fractionation related to differences in shell mineralogy.

Due to technical problems, only samples of more than 8 mg of $CaCO_3$ were analysed. Consequently only few analyses of single shells have been obtained restricting available information on intraspecific variability in isotopic composition. Such results, however, have been published by Vinot-Bertouille & Duplessy (1973). For two of the genera here under study (*Amphistegina* and *Operculina*) they found a scatter in isotopic composition of somewhere between 2 and 3‰ when about 40 individual shells from each species sampled at the same locality were analysed. These results emphasize the importance of using multiple-specimen samples when dealing with foraminifera.

The oxygen isotope composition of shell carbonate ($\delta^{18}O_c$) formed in equilibrium with the surrounding water is related to water temperature (T_w) as well as to isotopic composition of the water ($\delta^{18}O_w$) as reflected in the equation:

$T_w°C = 16.9 - 4.2\ (\delta^{18}O_c - \delta^{18}O_w) - 0.13\ (\delta^{18}O_c - \delta^{18}O_w)^2$ (actually the $\delta^{18}O_c$ is the oxygen isotope composition of CO_2 produced by the H_3PO_4 reaction of the carbonate and $\delta^{18}O_w$ is the oxygen isotope composition of CO_2 equilibriated with the water from which the carbonate precipitated) see Epstein et al. (1953) and Craig (1957).

No information is at present available on the isotopic composition of the water at the sample site. This is of minor importance, however, as the oxygen isotope composition of the molluscan shell carbonate is supposed to reflect the water composition, water temperature being the relating factor.

More important is the possibility of shell formation at varying temperatures. Other things equal, a shift in water temperature of 1°C will change the $\delta^{18}O_c$ value c. 0.25‰ (higher T_w leading to more $\delta^{18}O$ depleted carbonates). As seen from fig. 3, water temperature at Wadi Taba varies up to 4°C from summer to winter and from

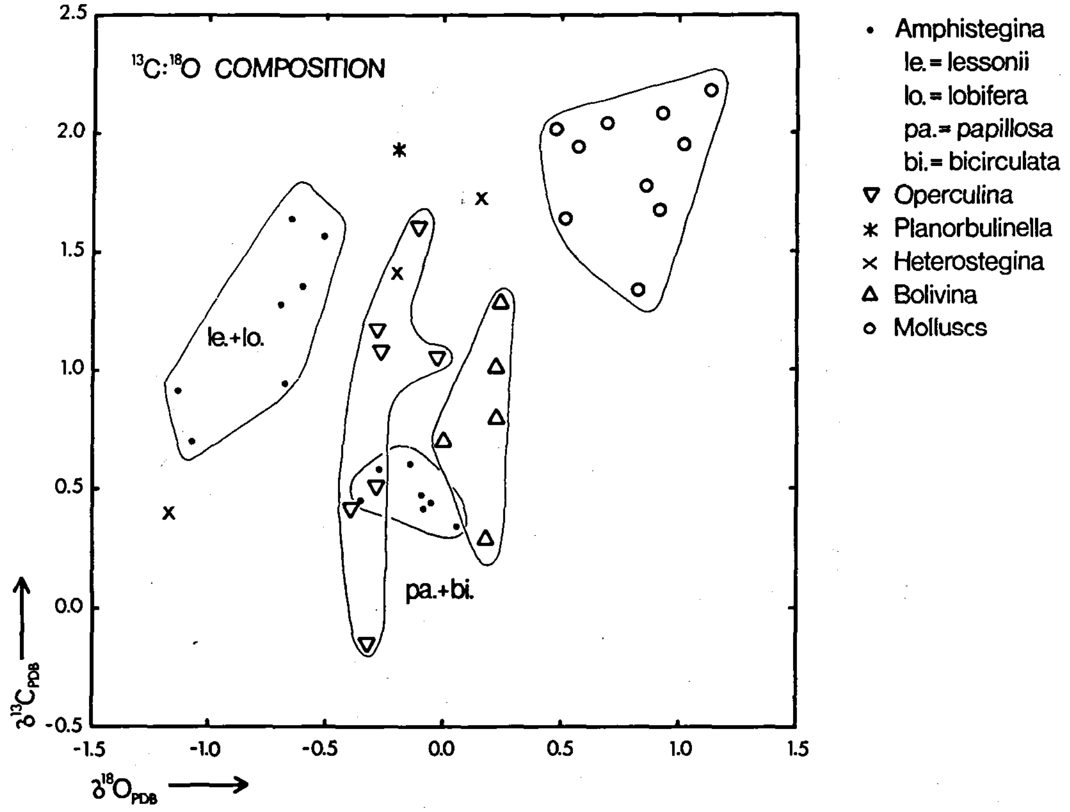


Fig. 4. The ^{13}C and ^{18}O composition of the investigated shell material. The values are not corrected for variations in growth temperature. Analytical precision better than ±0.1 ‰.

surface to 200 m depth. Provided that the molluscs grew their shells at a constant rate throughout the year, the annual mean water temperature at the water levels investigated can be used as a reasonable approximation for growth temperatures.

According to Larsen (1976), *A. lessonii* and *A. lobifera* have reproduction peaks in June and a lifespan of about a year. Assuming constant growth rates (cf. Larsen 1976) fullgrown specimens (c. 2 mm diameter) sampled in May will have grown their shells throughout the year. Therefore annual mean temperature is chosen as an approximation for average growth temperature in this group as well. No information is available on growth patterns for the other foraminiferal groups here studied.

In order to compensate for the observed temperature gradients, the $\delta^{18}O_c$ values have been "normalized" to values as if all shell material was formed at 21°C. This has been obtained by subtracting a value corresponding to the difference in isotopic composition between carbonate formed at the estimated growth temperature and at 21°C.

Still to be considered are the corrections due to isotopic fractionation between the different types of minerals formed by the organisms: aragonite in the molluscs and magnesian calcite in the foraminifera. According to Tarutani et al. (1969), a fractionation at 25°C of 0.6‰ was found to exist between inorganically precipitated aragonite and calcite (aragonite being 0.6‰ enriched in ^{18}O compared to calcite).

In connexion with the present study this fractionation will implicate a correction for the aragonitic $\delta^{18}O_c$ values (the molluscs) of −0.6‰ before comparison with calcitic data. The fractionation, however, has never been demonstrated to exist for biogenic calcite-aragonite

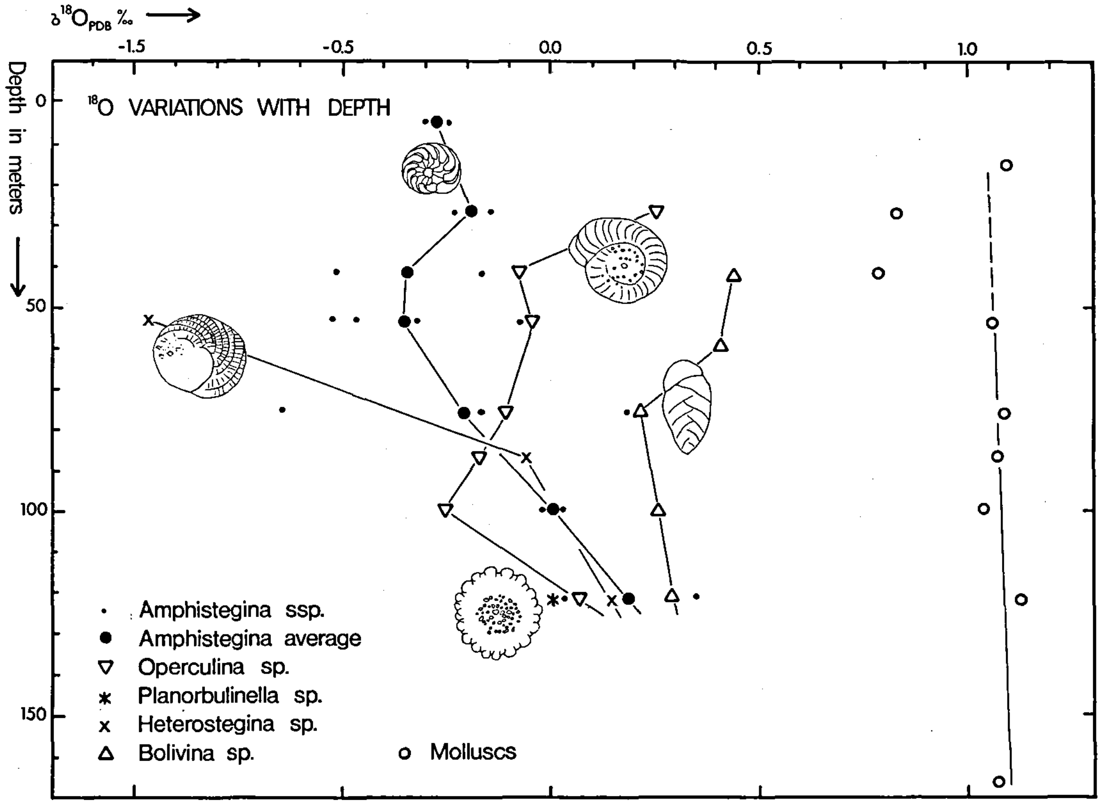


Fig. 5. The corrected ^{18}O variation of shell carbonate with depth. Analytical precision better than ±0.1‰.

pairs, and the $\delta^{18}O_c$ values shown in fig. 5 have not been subject to corrections. (Nevertheless it should be borne in mind that the molluscan values may be about 0.6‰ too heavy when compared to the calcitic foraminiferal data). Similar arguments can be applied to the ^{18}O enrichment found in inorganic magnesian calcites (Tarutani et al. 1969). According to these authors calcite is enriched in ^{18}O by c. 0.06‰ pr. mole $MgCO_3$. In the present study *Amphistegina* (4 mole % $MgCO_3$) and *Planorbulinella* (12 mole % $MgCO_3$) should thus be enriched in ^{18}O by 0.2 and 0.6‰ respectively when compared to normal calcite. Again such fractionations have not been found in biogenic carbonate (see e.g. Vinot-Bertouille & Duplessy 1973) and will not be considered here.

Fig. 5 illustrates what is believed to be 'true' isotopic differences between the carbonate secreting organisms studied. A clear ^{18}O depletion is found to affect all foraminiferal groups, smallest in the symbiont-free *Bolivina* group (c. 0.5‰) and greatest in the alga-carrying forms (up to 2‰), when compared to the molluscan carbonate. The effect is seen to be almost constant in size at all depth-levels as long as only the symbiont-free forms are considered. By contrast an ^{18}O trend towards increasing depletion and increasing scatter with decreasing depth seems to indicate that water depth may be an important factor affecting the amont of ^{18}O fractionation in the symbiont-carrying forms. Provided that molluscan shell carbonate does reflect the water/carbonate equilibrium fractionation, the observed ^{18}O depletion must be interpreted as caused by vital effects in the foraminiferal shell forming processes. Even if the formerly mentioned calcite-aragonite nonbiogenic fractionation is taken into account, the correction applied to the molluscan aragonite (c. 0.5‰) can only explain partly the observed differences – and only for the symbiont-free forms. The

Table 1. Oxygen isotope composition of shell carbonate from molluscs and foraminifera from the Gulf of Elat, Red Sea. The oxygen isotope composition is expressed as deviations in ‰ from the PDB standard, using the δ-function.

	Depth in metres										
Species	3.5 m	8 m	10 m	15 m	27 m	42 m	54 m	76 m	87 m	100 m	122 m
Bolivina sp.	–	–	–	–	–	+0.22	+0.22	–0.01	–	+0.12	+0.18
Operculina sp.	–	–	–	–	–0.11	–0.29	–0.26	–0.29	–0.32	–0.39	–0.03
Heterostegina sp.	–	–	–	–	–	–	–1.17	–	–0.21	–	+0.15
Planorbulinella sp.	–	–	–	–	–	–	–	–	–	–	–0.19
Amphistegina lessonii	–1.07	–	–0.69	–	–0.60	–0.38	–0.67	–0.83	–	–	–
A. lobifera	–1.13	–	–0.65	–	–0.51 –0.63	–0.73	–0.73	–	–	–	–
A. bicirculata	–	–	–	–	–	–	–0.44	+0.02	–0.03	–0.14	+0.25
A. papillosa	–	–	–	–	–	–	–0.27	–0.35	+0.06	–0.09	–0.07
Molluscs bulk sample	+0.51	+0.81	+0.69	–	+0.47	+0.57	+0.86	+0.92	+0.92	+0.91	+1.13

symbiont-bearing foraminifera still exhibit a depth related nonequilibrium ^{18}O depletion in the order of size of 0.4 to 1.6‰.

The possible existence of a vital effect in the symbiont-free foraminifera indicates that sources other than bicarbonate oxygen are available for shell formation in this group. Whether the effect can be ascribed to incorporation of metabolic CO_2, diffusion effects or to other origins cannot be concluded here. Nevertheless it is suggested that the additional ^{18}O depletion observed in the symbiont-carrying foraminifera must be related to physiological effects, the magnitude of which decreases with depth. Due to the homogeneity of the Gulf of Elat water the only important parameter changing with depth is light intensity. Variations in this parameter obviously control the photosynthetic activity of the symbiontic algae. It is therefore suggested that the shell-forming processes are affected by the algal photosynthesis, probably through incorporation of varying amounts of photosynthetic oxygen or other ^{18}O-depleted photosynthetic byproducts into the carbonate molecules in the shell.

When the carbon isotope composition of the investigated shell material is considered, corrections due to temperature gradients and possible calcite/aragonite fractionations are to be taken into account. According to Emrich et al. (1970) the temperature dependance of the $HCO_3^-/CaCO_3$ equilibrium fractionation is small (less than 0.1‰ pr. °C) and will not be regarded here. More important is the equilibrium fractionation between calcite and aragonite. Data given by Rubinson & Clayton (1969) suggest a ^{13}C-concentration in aragonite as compared to calcite precipitated under the same conditions by as much as 1.8‰ in inorganic experiments. It is not known, however, if this type of fractionation is of importance in the formation of biogenic carbonates.

Fig. 6 illustates the ^{13}C composition of

Table 2. Carbon isotope composition of shell carbonate from molluscs and foraminifera from the Gulf of Elat, Red Sea. The carbon isotopic composition is expressed as deviations in ‰ from the PDB standard, using the δ-function.

	Depth in metres										
Species	3.5 m	8 m	10 m	15 m	27 m	42 m	54 m	76 m	87 m	100 m	122 m
Bolivina sp.	–	–	–	–	–	+0.78	+1.28	+0.70	–	+0.99	+0.28
Operculina sp.	–	–	–	–	+1.60	+1.17	+1.07	+0.50	+0.12	+0.42	+1.05
Heterostegina sp.	–	–	–	–	–	–	+0.40	–	+1.42	–	+1.72
Planorbulinella sp.	–	–	–	–	–	–	–	–	–	–	+1.92
Amphistegina lessonii	+0.70	–	+1.28	–	+1.36	–	+0.94	–	–	–	–
A. lobifera	+0.91	–	+1.64	–	+1.39 +1.56	–	–	–	–	–	–
A. bicirculata	–	–	–	–	–	–	–	+0.41	–	+0.60	–
A. papillosa	–	–	–	–	–	–	+0.59	+0.45	+0.34	+0.47	+0.44
Molluscs, bulk sample	+1.64	+1.33	+2.05	–	+2.08	+2.18	+1.77	+1.95	+2.09	+1.66	+2.17

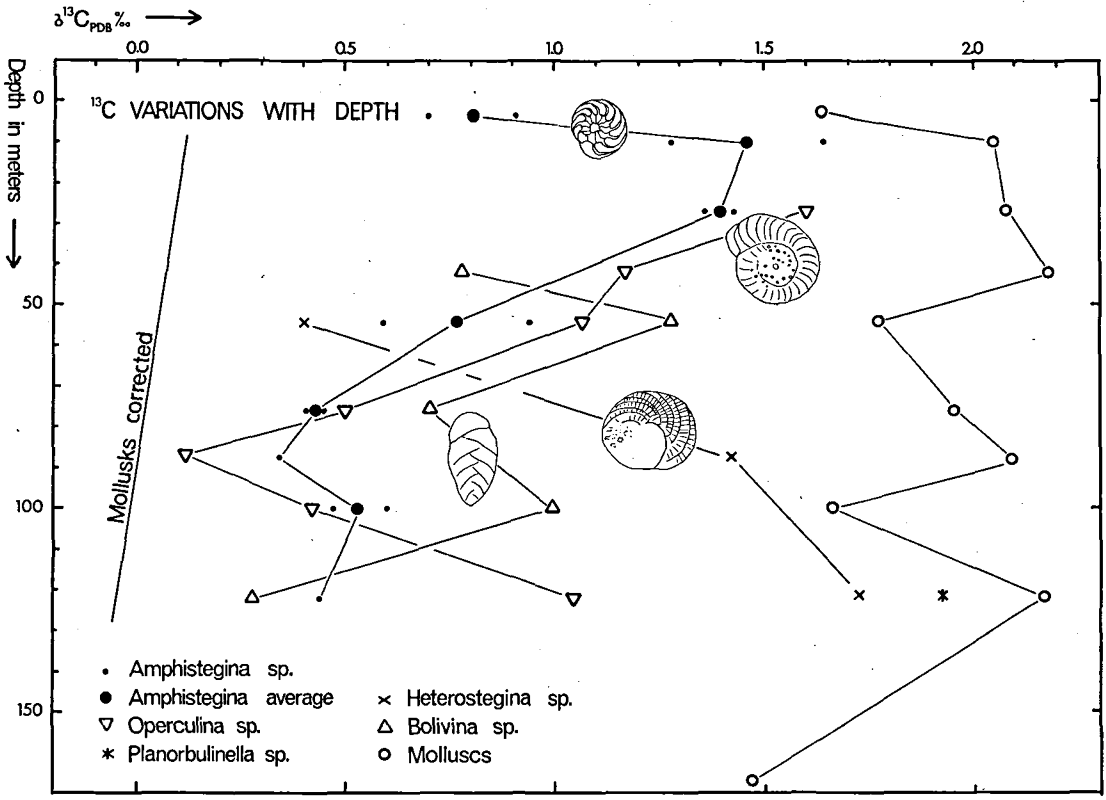


Fig. 6. The ^{13}C *variation of shell carbonate with depth. Analytical precision better than* ±0.1‰.

foraminiferal and molluscan shell carbonate, the latter values not corrected for the calcite/aragonite fractionation. In order to emphasize the magnitude of this fractionation, however, a line has been added representing the corrected ^{13}C molluscan values.

Except for the deepest station molluscan $\delta^{13}C$ values are seen to vary within relatively narrow limits (less than ±0.3‰), no trend with depth being observed. According to Mook & Vogel (1968) and Fritz & Poplawski (1974) molluscs incorporate ^{13}C into their shell carbonate at or close to isotopic equilibrium with dissolved HCO_3^-. Consequently the carbon isotope composition of bicarbonate dissolved in the water from the profile investigated is thought to be constant with depth. Unfortunately no direct measurements of $\delta^{13}C$ of dissolved bicarbonate are available.

From the figure it is obvious that most of the foraminifera analysed formed their shells out of isotopic equilibrium with the dissolved bicarbonate – regardless of corrections due to the possible calcite/aragonite fractionation. No difference is observed between symbiont-free and symbiont-bearing forms, both groups exhibiting a rather vague trend of decresing ^{13}C concentration with depth. The isotopic similarity between these two groups seems to exclude symbiosis as an explanation of the observed vital effects. At present no convincing explanation can be offered to clarify the ^{13}C uptake by the foraminifera here studied.

Summary and conclusion

The present study reports the oxygen and carbon isotope composition of shell carbonate precipitated by molluscs and benthic foraminifera collected over a depth profile in the Gulf of Elat, Israel. The foraminifera analysed consisted of both symbiont-free and symbiont-bearing forms. After corrections for temperature gradients with depth, the ^{18}O and ^{13}C composition of the molluscan carbonate show no significant variation with depth, a fact which indicates that isotopic composition of water and dissolved bicarbonate is close to constant over the profile investigated. Compared to these values the symbiont-free foraminifera exhibit a constant ^{18}O depletion by about 0.6‰ over the whole depth range, here interpreted as a vital effect. This effect is probably caused by incorporation of metabolic CO_2 into the shell carbonate. An additional ^{18}O depletion of up to 1.5‰ is observed in the symbiont-bearing species. Its positive correlation with light intensity suggests that photosynthetic oxygen produced by the symbiotic algae is a source in the formation of shell carbonate in this group together with dissolved bicarbonate and metabolic CO_2.

The establishment of an algal symbiosis/vital effect relationship in foraminifera emphasizes the difficulties in applying this type of organism to oxygen isotope palaeotemperature analyses. The photosynthetic influence further stresses the difficulties involved in correction procedures since corrections would be needed not only for the apparently constant ^{18}O depletions caused by the primary vital effect, but also for the additional, light-dependent effect.

On the other hand, the existence of large, light induced vital effects in symbiont-bearing foraminifera may prove to be valuable in palaeoecological studies. If similar, nonequilibrium vital effects can be identified in well preserved fossil benthic foraminifera, this may indicate the existence of a symbiotic relationship with algae in the specimens investigated and thus shell growth within the photic zone.

No well-defined differences in carbon isotope composition can be identified between symbiont-bearing and symbiont-free foraminifera. Nevertheless both forms are seen to form shells out of isotopic equilibrium with the dissolved bicarbonate. No satisfying explanation to this type of vital effect can be offered at the present stage of investigation.

Acknowledgements. Most of the isotopic analyses were carried out at the Geophysical Isotope Laboratory at the University of Copenhagen, the staff of which is greatly appreciated for their invaluable help. Thanks are due also to Dr. S. Savin, Case Western Reserve University, Cleveland, Ohio and to Dr. N. Shackleton, Cambridge University, England for providing additional analytical capacity. Dr. R. Bromley kindly improved the English text. This paper is published as part of a project financed by the Danish Natural Science Research Council.

Dansk sammendrag

Ilt- og kulstof-isotopsammensætningen af skalkarbonat fra bentoniske foraminiferer med symbiontiske alger i cytoplasmaet er blevet sammenlignet med den tilsvarende sammensætning af symbiontfri foraminiferer og af mollusker. Materialet er samlet på et dybdeprofil spændende fra 4 til 125 m dybde i Elat-bugten (Aqaba-bugten) i Israel. Efter korrektioner for temperaturvariation med dybden viste ^{18}O-indholdet i foraminiferskallerne karakteristiske forskelle set i forhold til molluskmaterialet. Under forudsætning af at molluskkarbonatet er dannet i isotopisk ligevægt med isotop-sammensætningen i de omgivende vandmasser, må det lavere ^{18}O-indhold i foraminiferkarbonatet skyldes biologiske processer, der ændrer isotopforholdet i skalmaterialet set i forhold til ligevægtsværdierne. Resultatet af sådanne processer betegnes almindeligvis isotopiske "vital-effekter". I det undersøgte materiale optrådte to typer af isotopiske vitaleffekter: et ^{18}O-underskud (i forhold til molluskmaterialet) af konstant størrelse (ca. 0.6‰) observeret hos samtlige foraminiferformer og et yderligere ^{18}O-underskud på op til 1.5‰ hos de symbiontbærende arter. Mens den første type vitaleffekt tolkes som forårsaget af små mængder metabolisk CO_2 indkorporeret i skalkalken, viser den anden types lysafhængighed, at det formodentlig drejer sig om et yderligere tilskud af fotosyntetisk dannet ilt til de skaldannende processer. Eksistensen af en lysafhængig vitaleffekt i symbiontbærende foraminiferer understreger vanskelighederne ved at benytte denne gruppe til isotopiske palæotemperaturmålinger.

References

Anderson, O. R. & Bé, A. W. H. 1976: The ultrastructure of a planktonic foraminifer, *Globigerinoides sacculifer* (Brady) and its symbiotic dinoflagellates. *J. Foram. Reseach* 6: 1–21.

Boltovsky, E. 1963: The littoral foraminiferal biocoenosis of Puerto Deseado (Patagonia, Argentina). *Contr. Cushman Fdn. foram. Res.* 14: 58–70.

Craig, H. 1957: Isotopic standards for C and O and correction factors for mass spectrometer analysis of CO_2. *Geochim. Cosmochim. Acta* 12: 133–149.

Duplessy, J. C., Lalou, C. & Vinot, A. C. 1970: Differential isotopic fractionations in benthic foraminifera and palaeotemperatures reassessed. *Science* 168: 250–251.

Emrich, K., Ehhalt, D. H. & Vogel, J. C. 1970: Carbon isotope fractionation during the precipitation of calcium carbonate. *Earth Planet. Sci. Lett.* 8: 363–371.

Epstein, S. Buchsbaum, R. Lowenstam, H. A. & Urey, H. C. 1953: Revised carbonate-water isotopic temperature scale. *Bull. geol. Soc. Amer.* 64: 1315–1326.

Fritz, P. & Poplawski, S. 1974: ^{18}O and ^{13}C in the shells of freshwater molluscs and their environments. *Earth Planet. Sci. Let.* 24: 91–98.

Grazzini, C. V. 1976: Non-equilibrium isotopic compositions of shells of planktonic foraminifera in the Mediterranean sea. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 20: 263–276.

Gross, M. G. 1964: Variations in the $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios of diagenetically altered limestones in the Bermuda Islands. *J. Geol.* 72: 170–194.

Hansen, H. J. 1975: On feeding and supposed buoyancy mechanism in four recent globigerinid foraminifera from the Gulf of Elat, Israel. *Revista Espanola de Micropal.* 7: 325–339.

Hansen, H. J. & Buchardt, B. 1977: Depth distribution of *Amphistegina* in the Gulf of Elat, Israel. *Utrect Micropal.* Bull. 15: 205–224.

Klinker, J., Reiss, Z. Kropach, C. Levanon, I. Harpaz, H. & Halicz, E. in press: Observations on the circulation pattern in the Gulf of Elat (Aqaba), Red Sea. *Israel J. Earth Sci.*

Larsen, A. R. 1976: Studies on Recent *Amphistegina*, taxonomy and some ecological aspects. *Israel J. Earth Sci.* 25: 1–26.

Lee, J. J., Freudenthal, H. D., Kossoy, V. & Bé, A. W. H. 1965: Cytological observations on two planktonic foraminifera *Globigerina bulloides* d'Orbigny, 1826, and *Globigerinoides ruber* (d'Orbigny, 1839) Cushman, 1927. *J. Protozool.* 12: 531–542.

Lowenstam, H. A. & Epstein, S. 1954: Paleotemperatures of the post-Aptian Cretaceous as determined by the oxygen isotope method. *J. Geol.* 62: 207–248.

Lowenstam, H. A. & Epstein, S. 1957: On the origin of sedimentary needles of the Great Bahama Bank. *J. Geol.* 65: 365–375.

McCrea, J. M. 1950: The isotopic chemistry of carbonates and a paleotemperature scale. *J. Chem. Phys.* 18: 849–857.

Mook, W. G. & Vogel, J. C. 1968: Isotopic equilibrium between shells and their environment. *Science* 159: 874–875.

Reiss, Z., Kropach, C., Levanon, I., Klinker, J., Harpaz, H., Shapiro, Y. and Ben-Avraham, Z. 1976: DCPE – Data collecting program in the Gulf of Elat. *In:* Reiss, Z. & Paperna, I.: *Fifth report of the H. Steinitz Marine Biology Laboratory, Elat, Israel,* 22–67.

Röttger, R. 1972: Die Bedeutung der Symbiose von *Heterostegina depressa* (Foraminifera, Nummulitidae) für hohe Siedlungsdichte ind Karbonatproduktion. *Abh. dt. zool. Ges.* 1971: 42–47.

Rubinson, M. & Clayton, R. N. 1969: Carbon-13 fractionation between aragonite and calcite. *Geochim. Cosmochim. Acta* 33: 997–1002.

Shackleton, N. 1974: Attainment of isotopic equilibrium between ocean water and the benthonic foraminifera genus *Uvigerina:* Isotopic changes in the ocean during the last glacial. *In:* Lalou, C. (ed.): *Les Méthodes quantitatives d'étude des Variations du Climat au Cours du Pleistocéne* 219: 203–209. Gif-sur-Yvette, France.

Shackleton, N., Wiseman, J. D. H. & Buckley, H. A. 1973: Nonequilibrium isotopic fractionation between seawater and planktonic foraminiferal tests. *Nature* 242: 177–179.

Tarutani, T., Clayton, R. N. & Mayeda, T. K. 1969: The effect of polymorphism and magnesium substitution on oxygen isotope fractionation between calcium carbonate and water. *Geochim. Cosmochim. Acta* 33: 987–996.

Vinot-Bertouille, A. & Duplessy, J. 1973: Individual isotopic fractionation of carbon and oxygen in benthic foraminifera. *Earth Planet. Sci. Lett.* 18: 247–252.

Walton, W. R. 1952: Techniques for the recognition of living foraminifera. *Contr. Cushman Fdn. Foram. Res.* 3: 56–60.

Weber, J. N. & Raup, D. M. 1966: Fractionation of the stable isotopes of carbon and oxygen in marine calcarious organisms – the Echinoidea. Part I & II. *Geochim. Cosmochim. Acta* 30: 681–736.

Weber, J. N. & Woodhead, P. M. J. 1970: Carbon and oxygen isotope fractionation in the skeletal carbonate of reef-building corals. *Chem. Geol.* 6: 93–117.

Palaeomagnetism of 4 dolerite dikes around Listed, Bornholm (Denmark)

NIELS ABRAHAMSEN

Abrahamsen, N.: Palaeomagnetism of 4 dolerite dikes around Listed, Bornholm (Denmark). *Bull. geol. Soc. Denmark,* vol. 26, pp. 195–215, Copenhagen, December 1st 1977.

Four dolerite dikes from the island of Bornholm have been investigated with the purpose of determining the palaeomagnetic pole positions and the magnetic ages, and to contribute to the general knowledge of the geological development of Bornholm. A total of 137 specimens were cored from 67 oriented hand samples from the dikes. After a.f. demagnetizations up to 1800 oe, three significantly different stable mean directions were isolated. The poles and Fisher statistics are for the Vaseaa dike 16°S, 128°E, $N = 11, \alpha_{95} = 9°$; for the Listed dike 14°N, 250°E, $N = 32, \alpha_{95} = 4°$; and for the Vigehavn dike 15°N, 159°E, $N = 7, \alpha_{95} = 6°$, while the Bölshavn dike gives two directions, a remagnetized direction A with a pole position of 13° N, 153° E, $N = 9, \alpha_{95} = 9°$, and a 'ghost' (supposed original) direction B with pole 21°N, 224°E. A comparison with known palaeomagnetic poles from Northwestern Europe and North America suggests that the palaeomagnetic data may be interpreted as follows: After cooling of the Svaneke granite the Vaseaa dike was probably injected around 1200 Myr. Some 200 Myr later the fault system was reactivated and injection of the Listed and Bölshavn dikes took place. Finally, the same fault system was reactivated once again in lower to mid-Palaeozoic time and the Vigehavn dike was intruded; at the same time the Bölshavn dike was partially remagnetized leaving only weak traces of the original direction of magnetization. During all the time covered, Bornholm was at fairly low latitudes, between 7° and 26°. By a reconstruction of the apparent polar wander curve it is argued that the polarity should be reversed for poles older than 1200 Myr to give a better fit of known data.

Niels Abrahamsen, Laboratoriet for geofysik, Aarhus Universitet, Finlandsgade 8, DK–8200 Aarhus N, Denmark. August 3rd, 1977.

The island of Bornholm, which covers an area of about 600 km², is situated in the Baltic Sea approximately midway between Sweden and Poland, fig. 1.

Bornholm is a rhomb-shaped horst bounded by faults and has a moderate relief. The geology of the island is closely related to the geology of south Sweden, the island being part of the Fennoscandian shield. Exposure of bedrock is minimal, more extensive exposures being restricted mainly to the NE-coast. About three quarters of the Pre-Quaternary surface consists of Precambrian gneisses and granites while the rest is covered by Palaeozoic and Mesozoic sediments (cf. fig. 1). Reviews of the geology are given by Milthers (1930), Noe-Nyegaard (1963) and Rasmussen (1966).

The purpose of the present paper is to present and discuss some palaeomagnetic results from the Listed and 3 minor dolerites dikes of E. Bornholm, the material of which was collected in 1969 and 1970.

Hitherto no palaeomagnetic results from Bornholm have been published, although the Kjeldseaa, the Kaas and the Listed dikes have been investigated by Schöneman (1972).

Geology

An early geosynclinal stage, with deposition of sediments and perhaps volcanics, was followed by metamorphism with the development of gneisses. Subsequently, the Rønne, Vang, Hammer, and Svaneke granites were formed (fig. 1). According to Micheelsen (1961) the Svaneke granite is the youngest post-kinematic granite on Bornholm.

All the gneisses and granites are Precambrian, as they are overlain by the Eocambrian Nexø sandstone. They are generally correlated with the Precambrian rocks of Gothian age in south Sweden, for which the radiogenic ages fall between 1400–1600 Myr. (Welin & Blomqvist 1966; Larsen & Springer 1976).

The formation of the basement gneisses and

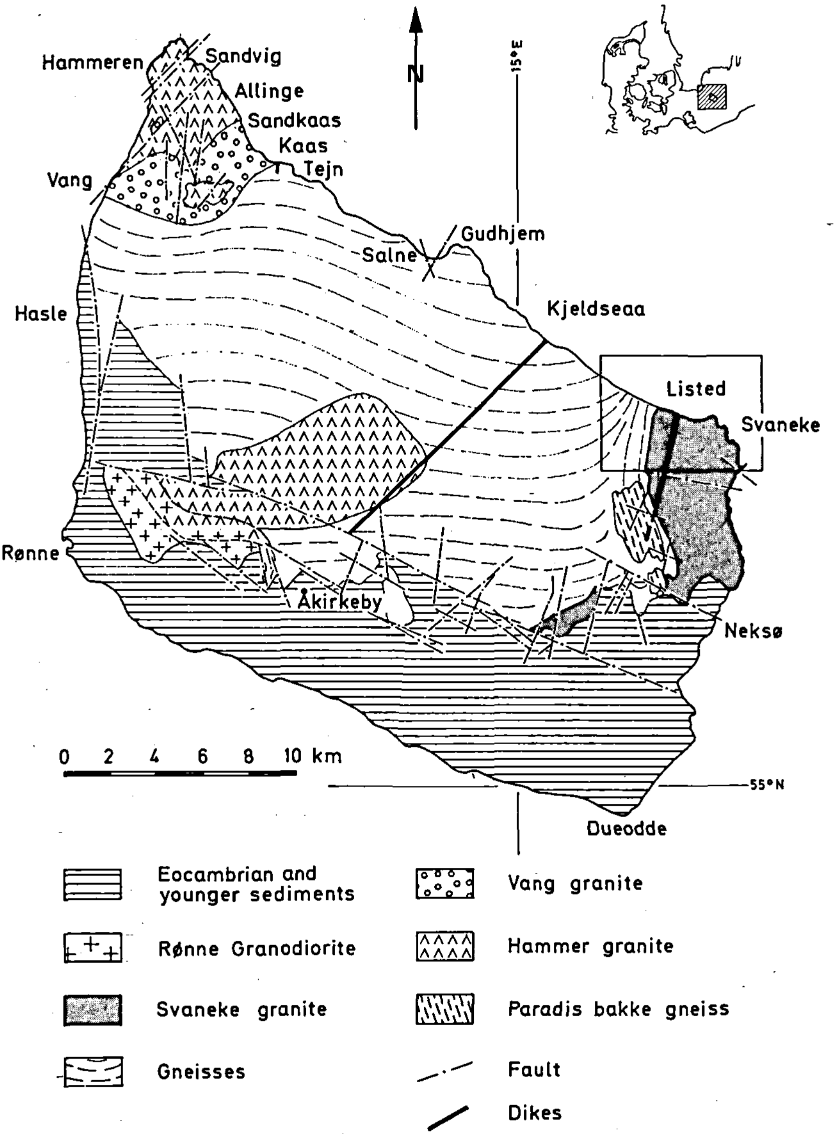


Fig. 1. Geological map of the island of Bornholm, Denmark (redrawn from Platou, 1970) with index map inserted at top.

granites was followed by a cratogenic period with faulting and injection of one or more generations of basic dikes. The dikes, although mostly narrow, are quite numerous in the basement (a number of 254 is given by Münther (1973)). They have never been observed cutting the Eocambrian or younger sediments. In south Sweden, post-Silurian NE–SW striking dikes, Permian NW–SE and WNW–ESE striking dikes, as well as Tertiary volcanic necks are numerous (Bylund 1974; Klingspor 1976).

Furthermore, the Svaneke granite and especially the Listed dike are cut by several sandstone 'dikes' of thicknesses varying from a few mm to 1.3 m (Ussing 1899; Bruun-Petersen 1975). The material of these 'dikes' closely resembles the clay- and iron-bearing, feldspar-poor, varieties of the Nexø sandstone. Therefore the sandstone 'dikes' are believed to be of the same age, formed by the entry of the unconsolidated Eocambrian sediment into opening fissures. This dates at least the Listed dike as pre-late Precam-

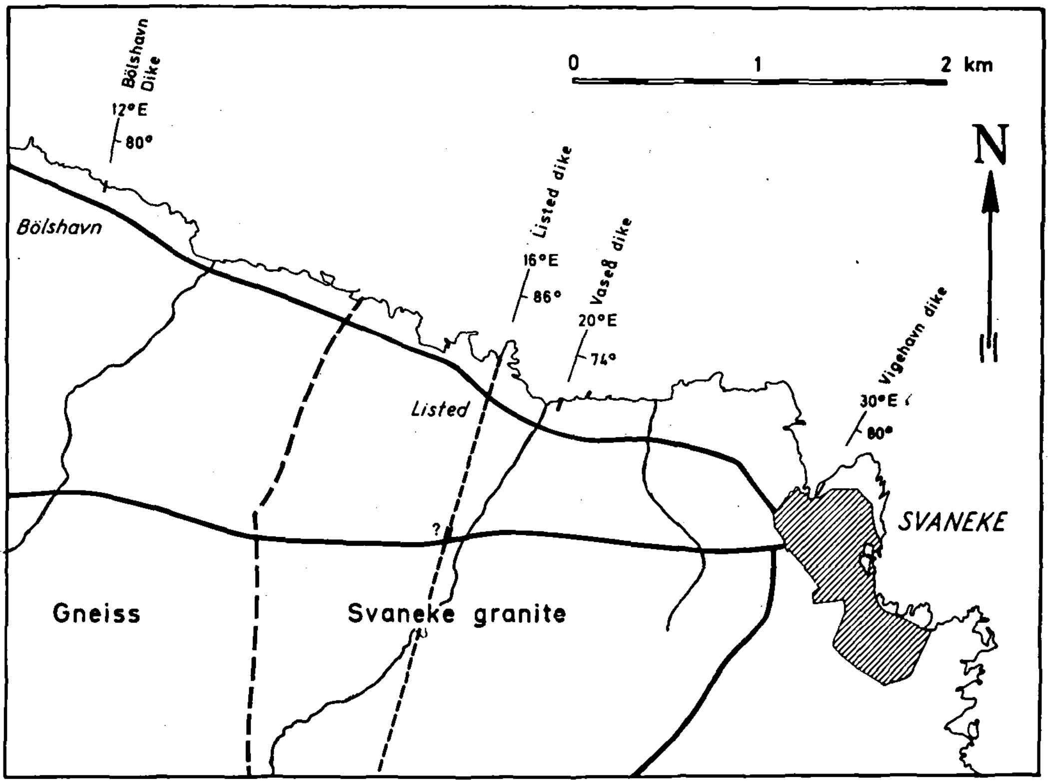


Fig. 2. Detailed map of the Listed-Svaneke area with the 4 dikes located.

brian. Finally, a single plagioclase crystal from the Kjeldseaa dike (fig. 1), 6 km WNW of Listed, has revealed a K/Ar-age of 1000–1100 Myr (O. Larsen, personal communication).

The three thick dikes, at Kjeldsaa (60 m), Kaas (40 m) and Listed (31 m), the highly altered dike west of Gudhjem at Salne Bay (22 m), as well as most of the many minor basaltic dikes (between 0.1 and 10 m wide), are all roughly vertical and strike between N–S and NE–SW. Strike directions of basaltic dikes between N–S and WNW–ESE, however, are known to occur at a few places, notably on the NW–coast at Jons Kapel south of Vang, but also at Hammeren (Callisen 1934), and Sandkaas (Münther 1945).

All the known mafic dikes are classified as olivine diabases, and they were believed by Callisen (1934) to belong to a single period of intrusion. However, as the dikes at Sandkaas appear to cut each other, and as a dike N of Allinge appears to have been offset prior to injection of another dike (Münther 1945), it is most likely that more than one period of injection took place. The time span involved is however difficult to estimate.

The fault pattern of Bornholm is quite complicated. At least the following, near-horizontal movements, in sequence of decreasing age, have taken place along faults striking 1) N–S, 2) NE–SW, 3) N–S or NNE–SSW and 4) NE–SW, the horizontal displacement of 2) being at least 400–500 m (Münther 1945). Most of the present day straight narrow valleys (so-called 'sprækkedale') are located in glacially eroded ancient zones of movements, many of which are mylonite zones. Some were intruded by basic dikes, like the Listed dike (in Tamperdal) and the Kjeldseaa dike (in Ekkodalen). After injection, some of the dikes have been jointed, making them rather susceptible to alterations and erosion.

A detailed map of the Svaneke-Listed-Bølshavn coast is given in fig. 2 including location, strike and dip of the 4 dikes investigated. Only the major (Listed) dike has been located away from the coast.

a) Listed dike

The 30–31 m wide Listed dike is well exposed in the coast at Gulehald 200 m east of Listed harbour where it intrudes the Svaneke granite (type I, Platou (1970)). A continuation of the same dike (20 m wide) occurs 5 km south of Listed in the Paradisbakke gneiss in Tamperdal. The hidden dike has been traced gravimetrically (Saxov 1959) and magnetically (Münther 1973).

The Listed dike (Jensen 1966) is of basaltic composition with a doleritic to subdoleritic texture. Plagioclase crystals (~ An50) become slightly more calcic, and the % Al_2O_3 in the rock increase slightly towards the centre of the dike and are supposed to be due to an increase in water pressure during crystallization. Apart from a dense chilled zone a few mm thick, the dike margins (1–3 m) are slightly more finegrained than the central parts. The mafic silicates, as well as the ore minerals, are rather strongly altered, the sequence of crystallization being ilmenite, titanomagnetite, olivine, pyroxene, plagioclase and possibly quartz and biotite.

The history of the opaque minerals (4.5 – 5 Vol. -%) is quite complicated (Jensen 1966). Above 600–700°C primary homogeneous titanomagnetite (with an initial composition between 30–40% Fe_3O_4, 70–60% Fe_2TiO_4) underwent oxidation exsolution processes to form ilmenite, ulvöspinel and very fine-grained magnetite with homogeneous areas less than 1 μ in width. Ilmenite (96% $FeTiO_3$, 3% Fe_2O_3, 1% $MnTiO_3$) was subsequently formed from ulvöspinel. The sulfide content is quite low, $\leqq 0.2\%$.

Alterations commonly include various degrees of oxidation of titanomagnetite to turbid sphene containing very small remnants of probably unaltered magnetite; at the margins. ilmenite has been oxidized to rutile. In a very few cases alterations along thin cracks of titanomagnetite to maghemite were also observed.

Apart from the observed alteration to maghemite, the mineral alterations are presumed to have taken place during or shortly after crystallization and cooling of the dike (Jensen 1966). The only (younger) hydrothermal activity known from the area is the very minor sulfide mineralizations from the Nexø sandstone reported by Pauly (1944).

Based on the Fe-Ti-oxides as a thermometer, an initial temperature of cooling from above 950°C is indicated, which seems reasonable for a basaltic magma crystallizing under hypabyssal conditions (Jensen 1966).

The lattice constant for the titanomagnetite was found to be 8.396 Å, corresponding to nearly pure magnetite with Curie temperature around 570–575°C. By means of a low-field susceptibility bridge, the Curie temperatures of powder specimens were found to be around 570°C (fig. 3).

To estimate the cooling time (e.g. Jaeger 1968) of the Listed dike we may suppose the thermal diffusivity of the dike and the surrounding granite to be 0.01 $cm^2\ s^{-1}$, and the initial temperatures of the dike and granite to be 1050 and 50°C, respectively (corresponding to a superficial injection into the upper 1–3 km of the Earth's crust with a normal geothermal gradient of 20–30°C/km). It would then take the 30 m wide dike 100–200 y to cool below 200°C, and 1000–3000 y to cool below 100°C, where most of the initial mineralogical transitions have occurred. Hence we conclude that the primary thermochemical RM of the Listed dike was acquired in a geologically short time, which, however, was probably long enough to smooth out the geomagnetic secular variations.

b) Vigehavn dike

The 20–40 cm wide dike is exposed in Vigehavn 550 m north of Svaneke church (fig. 2). The porphyritic diabase appears very fresh in outcrop, being black and fine-grained, but thin section studies show that it may locally be rather strongly altered (Callisen 1934, Locality Nørrevig). Phenocrysts (1–3 mm) are plagioclase (An 62%), olivine and augite. The olivine is partly serpentinized with magnetite and occasionally picotite. Augite, biotite and magnetite are abundant. Small nodules of calcite and chlorite with epidote and quartz are found. The Curie temperature was around 570°C (fig. 3), corresponding to nearly pure magnetite. The finegrained, narrow dike must have cooled rapidly, the primary magnetization being of thermal origin. The carriers of the characteristic remanent direction representing less than 0.2% of the

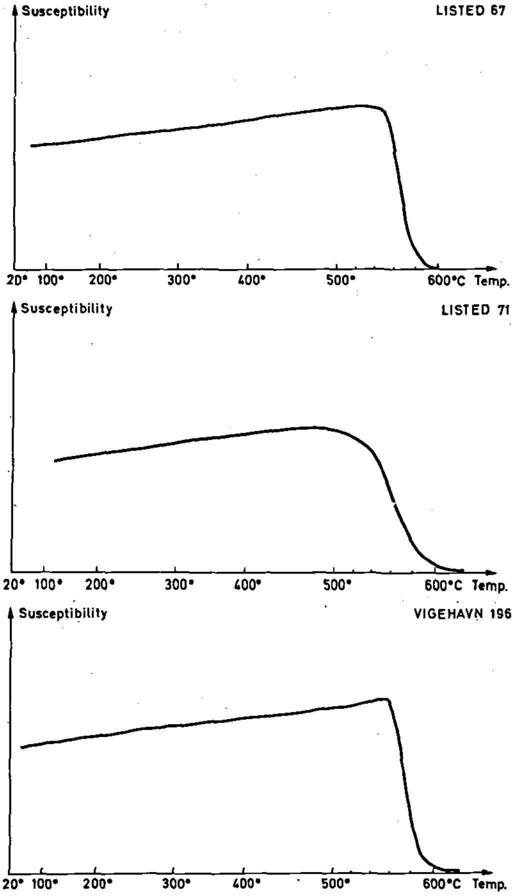


Fig. 3. Susceptibility (relative) versus heating of powder specimens, showing Curie points around 570°.

NRM intensity may well be a later induced CRM in the fine-grained magnetite of the serpentinized olivines.

c) Vaseaa dike

The 1½ m wide dike is well exposed at the coast, 50 m E of the outlet of the brook Vaseaa 1 km E of Listed harbour (fig. 2), intruded into Svaneke granite (type II; Platou 1970).

The dike (Callisen 1934) is an olivine diabase porphyrite with plagioclases (An 65%) in fist-sized aggregates with single crystals attaining a length of 2–3 cm. These are rather sericitized or epidotized, with interstitial chlorite and serpentine. The matrix is fine-grained, black green and rather altered with augite, plagioclase, olivine pseudomorphs, some opaque minerals, brown hornblende and biotite. Some spherules are filled by chlorite and calcite.

As the cooling time of a dike is proportional to the square of the width, and the width of the Vaseaa dike is $^1/_{20}$ of that of the Listed dike, the cooling time must have been of the order of 1 y, all physical parameters being identical.

d) Bølshavn dike

The dike is about 3 m wide, exposed in the coast 300 m east of the small harbour at Bølshavn, and intruded into a grey biotite-rich gneiss (fig. 2). The diabase (Callisen 1934) is a porphyritic, grey green rusty dike, the colour of which is partly due to decomposition of ore minerals. Many small fissures and joints are filled with calcite. The matrix is fine-grained and highly altered, with abundant small grains of iron ore. The phenocrysts are augite, serpentine pseudomorphs after olivine with amphibole needles, opaque grains and occasionally small grains of sphene.

Along the western contact (the eastern contact is poorly exposed) the gneiss has been subjected to contact metamorphism up to a distance of 3½ m from the contact, the dark minerals of the gneiss being partly chloritisized and partly altered to a rust-coloured material, which by invasion along small joints gives the gneiss a red-brown colour. This thermal effect is well kown,

Table 1: NRM intensity Jo,susceptibility κ and Königsberger Ratio Q.

	N	Jo 10^{-5} emu/cc) Geometrical mean	range	κ (10^{-5} G/Oe) Geometrical mean	range	Q = Jo/κF mean
Listed dike	36	61	33–125	132	22–218	0.92
Listed, non-typical salic parts	7	0.44	0.2–1	~20		<0.08
Vigehavn dike	7	3780	1000–7100	112	77–177	68
Vaseaa dike	12	21	2–100	136	52–200	0.30
Bölshavn	13	8.6	4–16	25	17–42	0.68

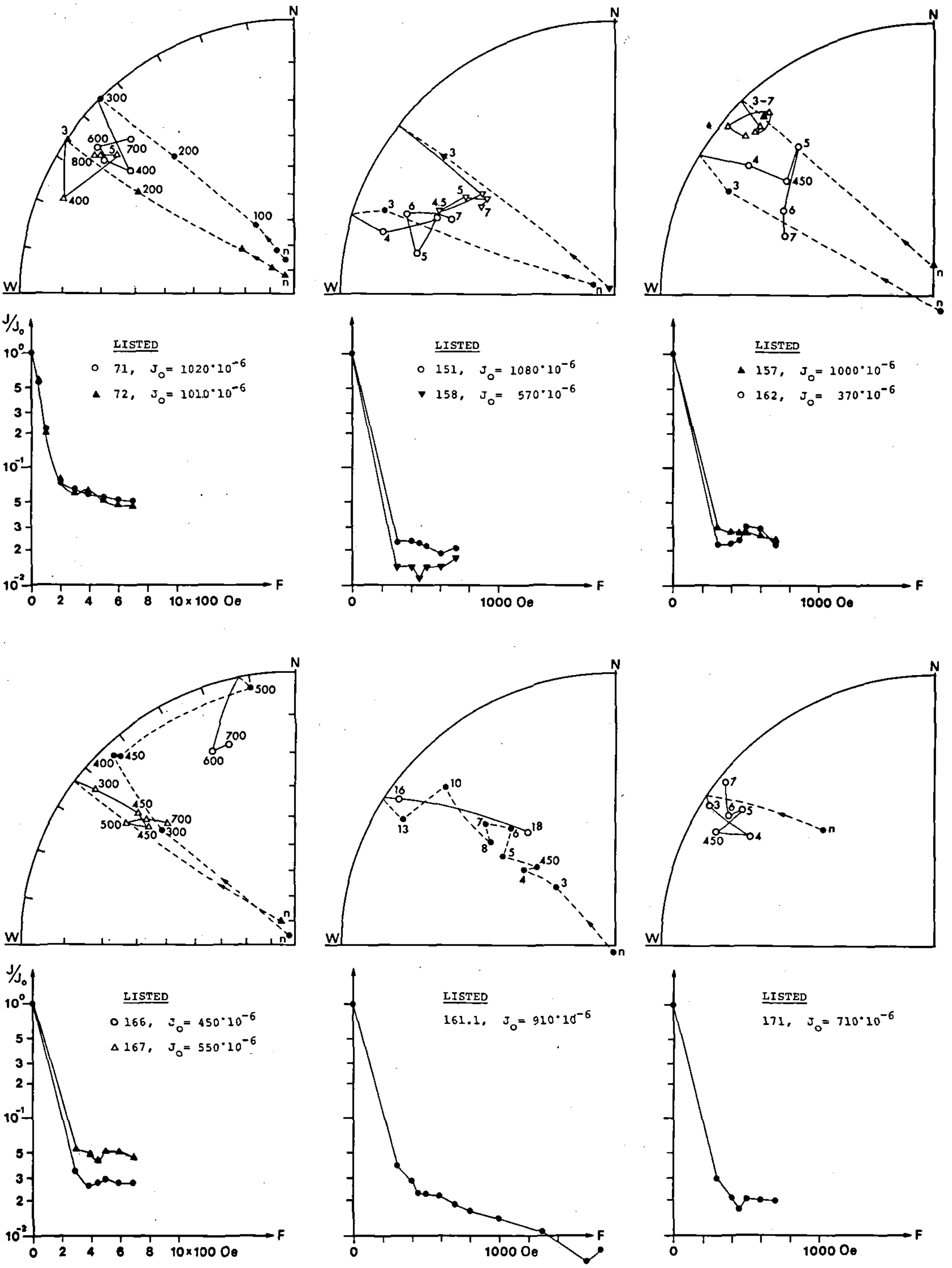


Fig. 4a. Listed dike: Examples of alternating field demagnetizations; numbers indicate Oe peak fields (× 100). Solid (open) symbols indicate positive (negative) inclinations.

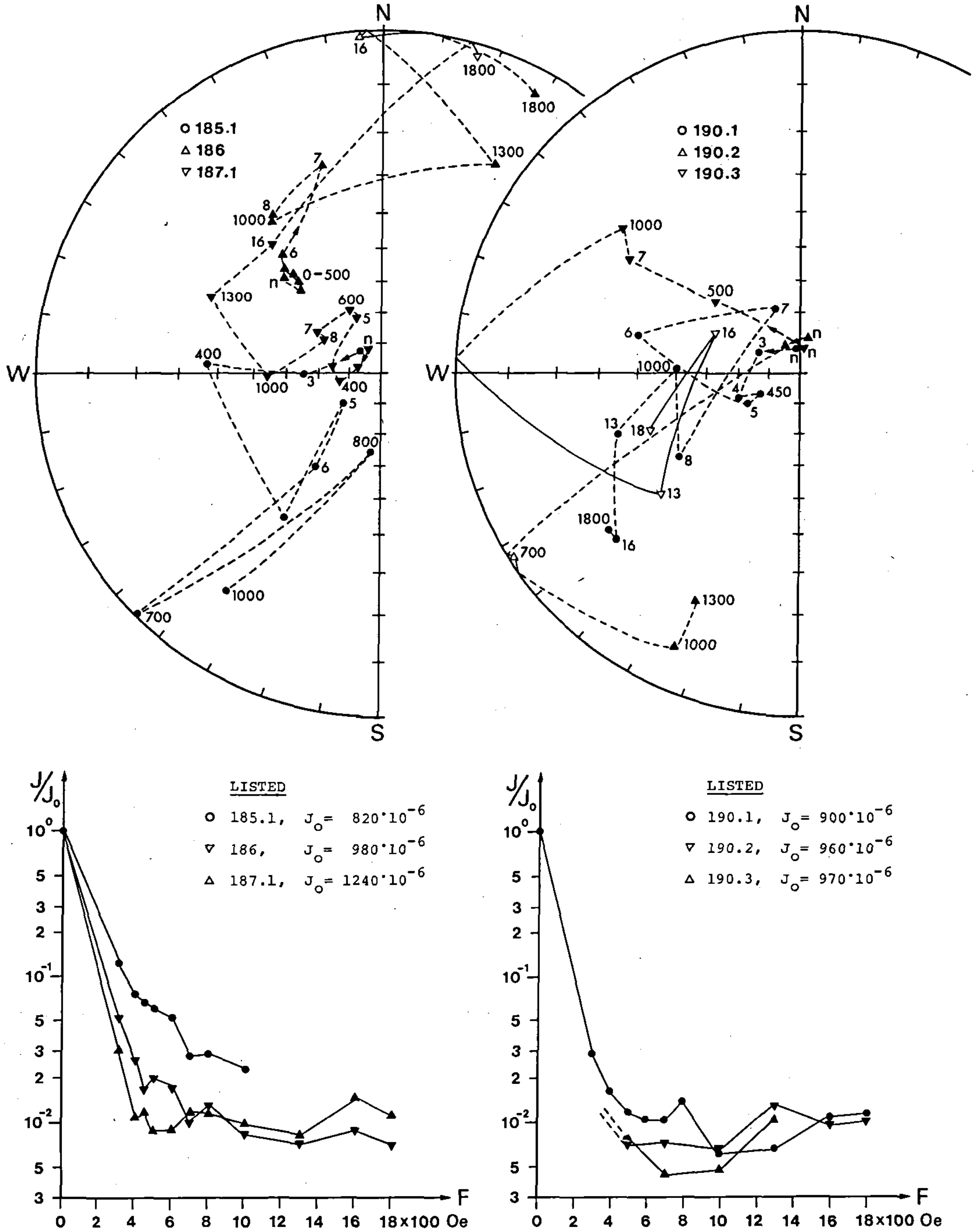


Fig. 4b. Listed dike: Demagnetizations of supposed remagnetized samples.

Table 2: Mean of a.f. demagnetized stable directions.

								Pole Position			
	N	F	Decl.	Incl.	k	α_{95}	R	Lat.	Long.	δp.	δm
Listed dike:		Oe									
Unit weight to sample	36	400–1800	302.4°	–10.0°	12.3	7.1°	33.1752	13.5°N	254.8°E	3.6°	7.2°
U.w. to sample, excl. no. 185, 186, 187 & 190	32	400–1300	306.6	–13.8	38.9	4.1	31.2050	13.8°N	250.1°E	2.1	4.2
U.w. to specimen, excl. no. 185, 186, 187 & 190	44	400–1300	306.3	–13.6	36.1	3.6	42.8106	13.8°N	250.4°E	1.9	3.7
Listed + Bölshavn B	50	400–1800	309.3	–14.5	25.6	4.1	48.0885	14.7°n	247.4°E	2.2	4.2
Vigehavn dike:											
Unit weight to sample	7	400–1300	35.8	–25.7	97.4	6.1	6.9384	15.0°N	158.8°E	3.6°	6.6°
Unit weight to specimen	14	400–1300	34.8	–26.2	72.3	4.7	13.8204	15.1°N	159.8°E	2.8	5.1
Vaseaa dike:											
Unit weight to sample	12	200–500	85.3	–43.0	17.1	10.8	11.3588	17.7°S	123.5°E	8.3°	13.4°
Unit weight to specimen	25	200–500	88.2	–44.5	13.9	8.0	23.2757	20.2°S	122.0°E	6.3	10.1
U.w. to sample, excl. no. 132	11	200–500	80.6	–44.2	27.6	8.9	10.6373	16.0°S	127.8°E	6.3	10.0
Bölshavn dike:											
A: Unit wight to sample excl. no. 201	12	500–800	31.1	–22.1	10.8	13.8	10.9833	18.5°N	162.7°E	7.7°	14.6°
U.w. to sample excl. 201, 207, 213 & 215	9	500–800	42.2	–25.5	34.1	8.9	8.7657	12.8°N	152.9°E	5.2	9.6
B: 207.1	1	700	330	–6							
207.2	1	700	328	–16							
208.1	1	1000	333	–29							
213.3	1	600	327	–38							
215.1	1	700	351	–13							
215.2	1	1800	317	–16							
Unit weight to specimen	6		333	–20	25.5	13.5	5.8045	20.7°N	223.6°E	7.4	14.1

e.g. from dikes in South Sweden, but it is not often encountered with the small dikes of Bornholm. Although the degree of metamorphism is small, the width of the zone affected is considerable in comparison with the moderate width of the dike, and especially in comparison with the broader dikes without such effects (Callisen 1934).

The cooling of the Bølshavn dike (which is only $^{1}/_{10}$ as wide as Listed dike) must have occurred within a few years, all other parameters being equal, so an original TRM would represent a magnetic spot reading in time with little secular smoothing.

Palaeomagnetic results

Several oriented hand samples were collected from each dike. The orientation was marked on a horizontal surface of plaster of Paris using a magnetic compass combined with topographical control sights. 1-inch specimens were later drilled from each sample and measured on a Digico spinner magnetometer.

In the field the susceptibility was measured in situ with a portable susceptibility meter of the bridge type. These results are summarized in table 1, together with the intensity of NRM and the Koenigsberger ratio. Except for the Vigehavn dike the Q-values are generally low, suggesting low coercivities.

a) Listed dike

A total of 43 hand samples were collected from the coastal exposure. 7 of the samples from a local non-typical part of the dike with resorbed granitic material (Callisen 1934) were abnormally weakly magnetized. The directions after demagnetization were very scattered, and they are not considered further.

After some pilot demagnetization experi-

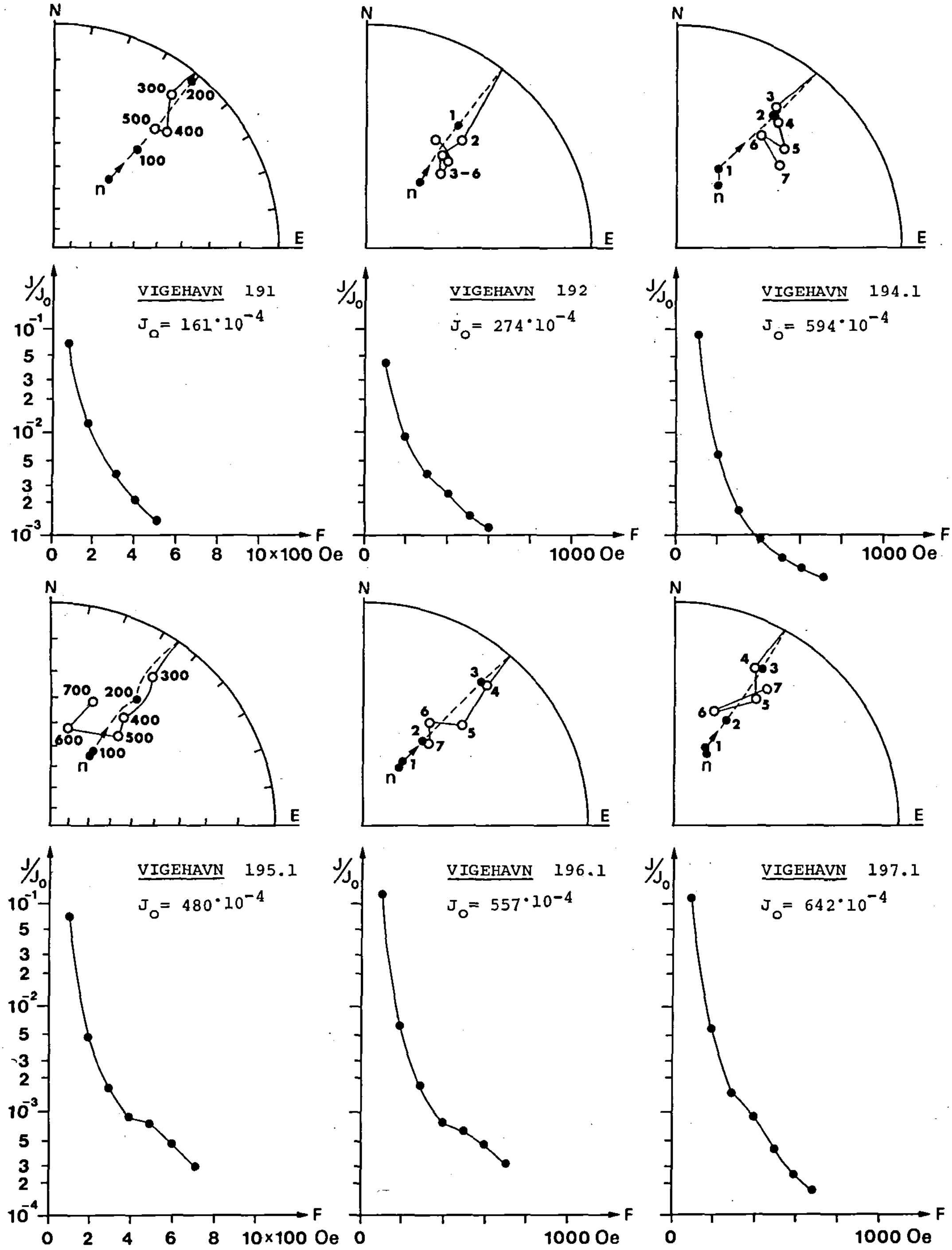


Fig. 5. Vigehavn dike: Examples of a.f. demagnetizations.

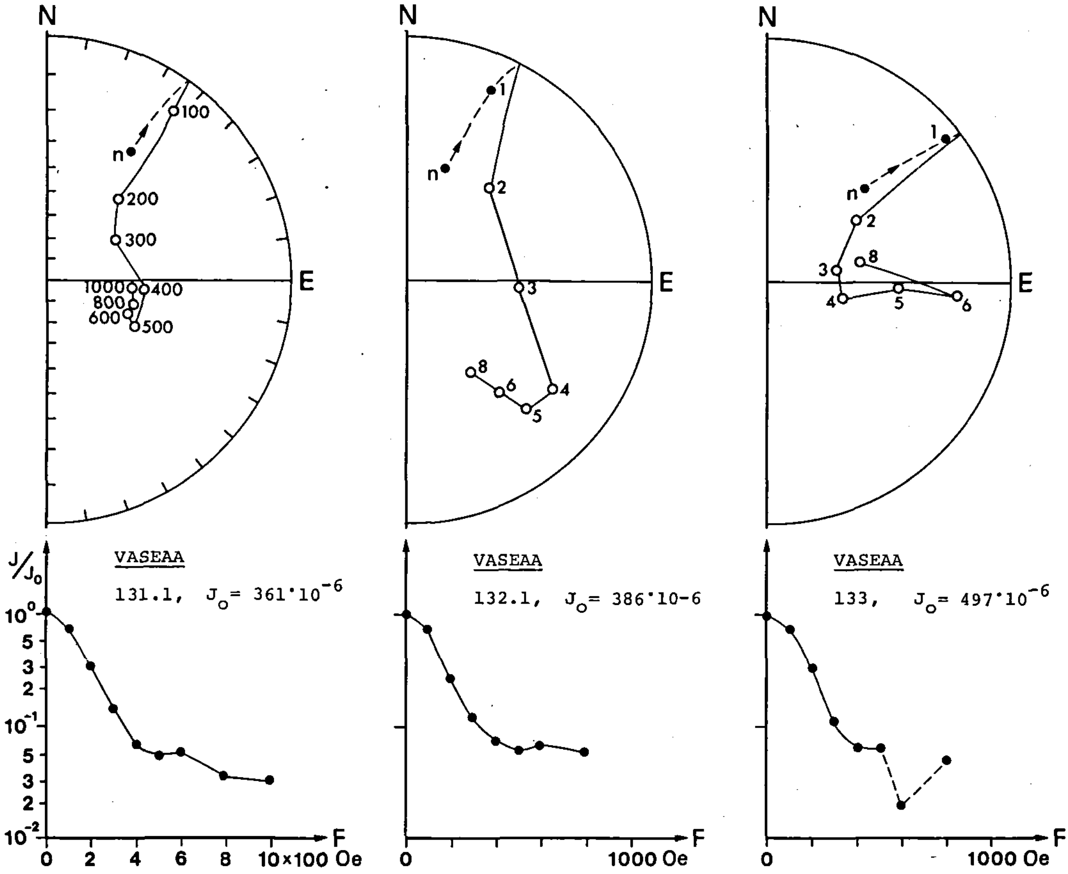


Fig. 6 a, b, c. Vaseaa dike: Examples of a.f. demagnetizations. (Continued on pp. 205 & 206).

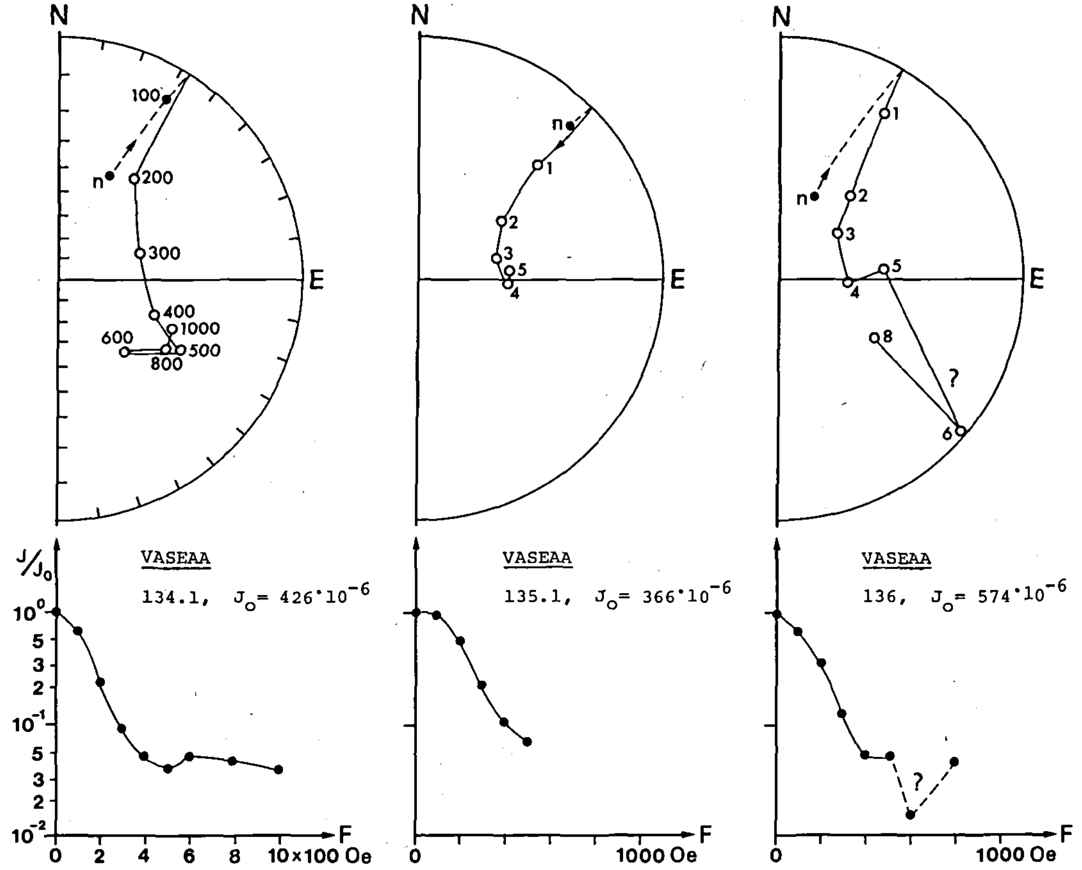
ments, all the remaining specimens were progressively a.f. demagnetized in zero field (± 10 γ), and the remaining RM (remanent magnetization) measured. The median destructive field (m.d.f.) was typically around 50Oe, and in most cases a characteristic, cleaned direction was found for a demagnetizing field around 400–600 Oe peak, as illustrated in fig. 4 a; the remaining remanence intensity was typically between 0.5 and 5% of the NRM. The mean of the characteristic, cleaned direction with unit weight to samples and specimens are listed in table 2.

In some cases the RM, however, was more stable, and demagnetizing fields between 1000 and 1800 Oe were necessary to retrieve the characteristic component (e.g. fig. 4 a, No. 161.1). In four samples (Nos. 185, 186, 187, 190 in fig. 4 b) the RM was also stable but the inclination remained positive during demagnetization. This may be due to remagnetization caused by chemical alteration in the Palaeozoic, as the steep, positive inclination may be the result of two sub-components with NNE and SSW declination, acquired in a Palaeozoic field direction.

All the cleaned directions and their mean direction are shown in fig. 8 a for the Listed dike: Dm, Im = 306.6°,−13.8°; α_{95} = 4.1°, N = 32° (Fisher 1953). When ignoring the 4 samples mentioned above, the directions are fairly symmetrically grouped showing that the characteristic RM of the dike has a simple structure with a well determined mean direction.

b) Vigehavn dike

From each of 7 hand samples 1–3 specimens were cored and a.f. demagnetized in steps of 100



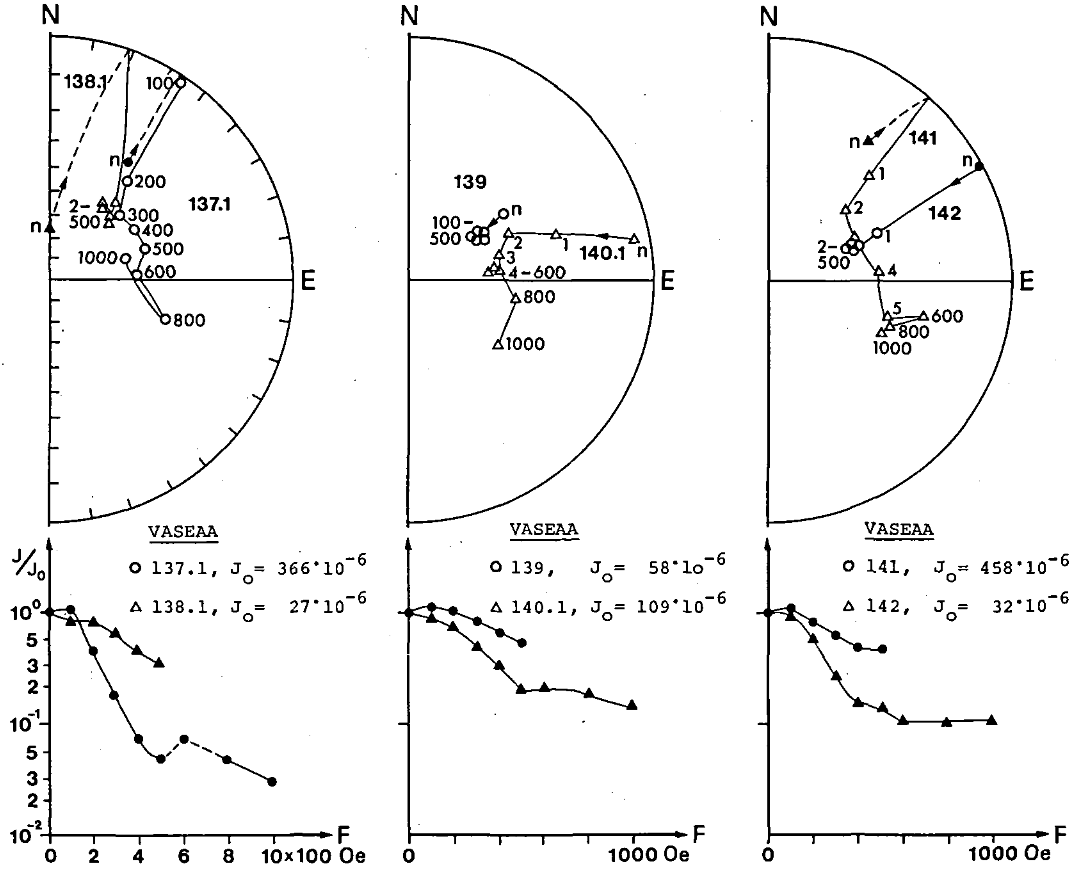
Oe. The NRM intensity was quite high (table 1), whereas the m.d.f. was 50–100 Oe. Representative examples of the demagnetizations are drawn in fig. 5, showing that characteristic RM directions are typically found for peak fields between 400 and 700 Oe. The RM directions of sample means are plotted in fig. 8 b showing a good grouping around the mean Dm, Im = 35.8°, -25.7°; α_{95} = 6.1°; N = 7 (table 2).

As the dike is strongly magnetic, an estimate of a possible refraction error according to $i_o = \frac{1}{\mu} \cdot \tan i_r$ was made (i_o being the angle of incidence of the magnetic field $\bar{H}$, i_r the refraction angle of the magnetic induction $\bar{B}$ inside the dike and μ the magnetic permeability of the dike). The maximum possible refraction error for the dike was found to be $\Delta i = i_r - i_o = 4.4$ at an angle of incidence of 45°. The actual angle of incidence was however only ~ 10°, giving a mean refraction error of 1.6°, which is insignificant when compared with α_{95}.

c) Vaseaa dike

From the dike 12 oriented hand samples were collected, and 1 to 3 specimens were cut from each. The m.d.f. ranged between 150 and 500 Oe. One specimen from each sample was a.f. demagnetized in steps of 100 Oe as shown in fig. 6. The stable directions usually occurred in peak fields between 300 and 500 Oe and most of the remaining specimens were demagnetized at 500 Oe. The resulting means of all samples are shown in fig. 8 c and the mean listed in table 2.

11 of the sample means (22 specimens) group rather well, although the cluster is somewhat elongated, whereas especially one sample



(specimens Nos. 132.1, 132.2 and 132.3) deviates considerably from the mean. Rejecting this, the mean of cleaned sample directions is Dm, Im = 80.6 °, –44.2°; α_{95} = 8.9, N = 11.

As the dike is rather strongly altered (pseudomorphs from olivine, interstitial chlorite and serpentine), the cleaned mean direction above could be a smoothed direction, intermediate between two directions, the Vigehavn and a reversed Listed direction, which were blocked at different times. One direction (close to the Vigehavn) is seen most clearly in samples Nos. 138.1, 139, 140.1 and 142, while the change in direction on demagnetization in fields above 3–400 Oe of Nos. 131, 132, 134, 137, 140.1 and 141 may indicate a subcomponent in an approximate direction around or beyond that of No. 132 (close to a reversed Listed direction). Because of the higher coercivities the carriers of the latter direction are probably more fine-grained magnetites than those of the former direction.

d) Bølshavn dike

From 13 oriented hand samples 1–3 specimens were drilled (except No. 216, from which 13 specimens were cut), and one pilot specimen from each sample was a.f. demagnetized in steps of 50–100 Oe, before the rest were demagnetized at 500 to 800 Oe. Typical examples are shown in fig. 7 a. The m.d.f. was between 50–100 Oe. During demagnetization most directions stabilized at F = 500–600 Oe, the mean directions of which are plotted in fig. 8 d. One sample (2 specimens, No. 201) had an extremely stable magnetization direction close to the present Earth's field, and the direction changed only slightly up to the

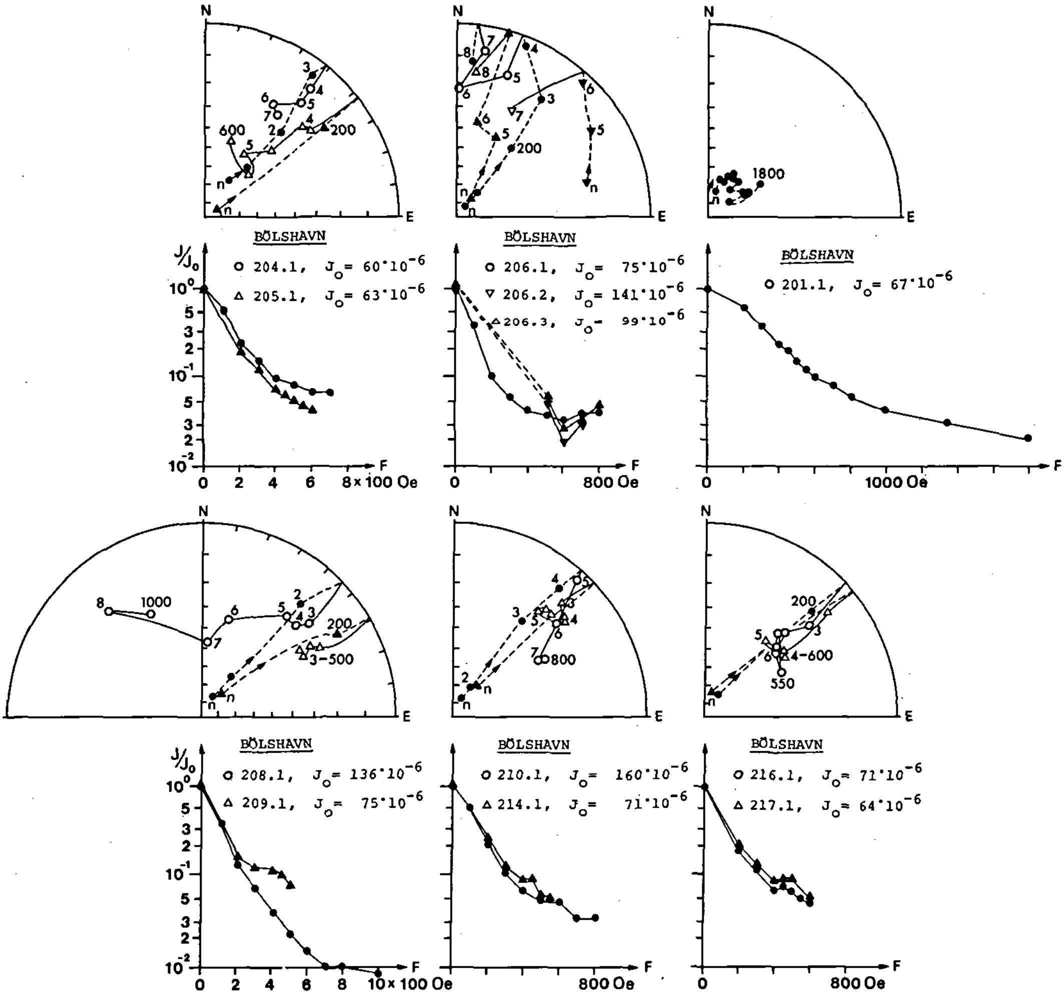
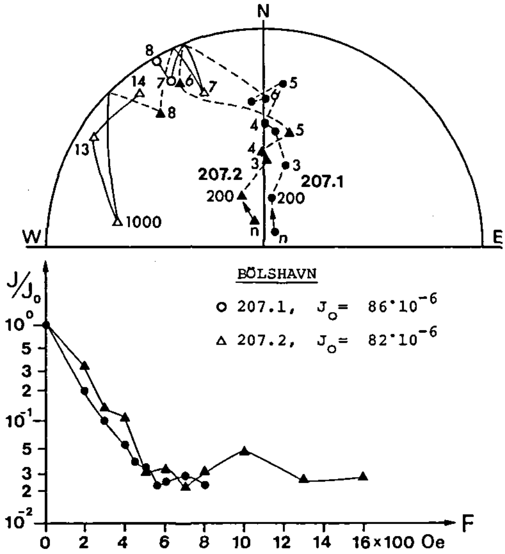


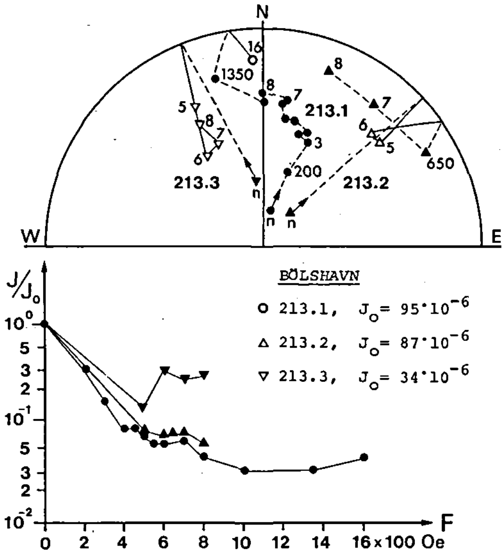
Fig. 7 a, b. Bölshavn dike: Examples of a.f. demagnetizations. (Continued on p. 208).

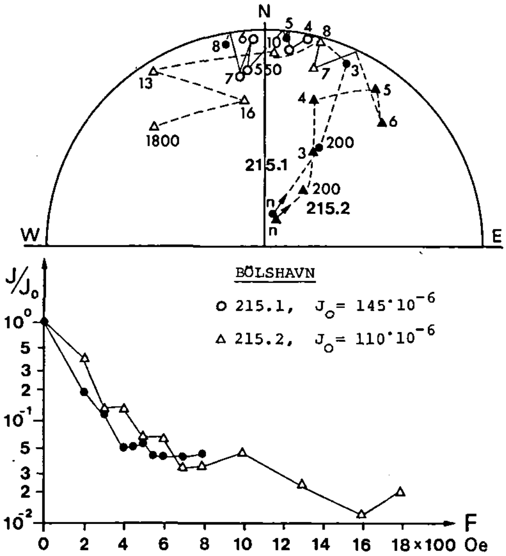
maximum attainable field of 1800 Oe peak. As it behaves quite differently from the other samples, it was excluded from the mean value (table 2).

The remaining 12 samples (46 specimens) show a cleaned direction at moderate field strength between 500–700 Oe (direction A), whereas 4 samples (9 specimens), Nos. 207, 208, 213 and 215 (fig. 7) and to a certain degree No. 206 (3 specimens) obviously reveal 2 magnetic directions during the a.f. cleaning; direction A with moderate and direction B with higher coercivities.

The best estimate of direction A is given by the 9 samples (table 2) which are plotted in fig. 8 d with Dm, Im = 42.2°, -25.5°, α_{95} = 8.9°, whereas the best estimate of the more diffuse direction B is given by the 6 specimens of table 2 as Dm, Im = 332.9°, -20.1°; α_{95} = 13.5° (fig. 8 d). Because of the alterations at least one, and possibly both components may be of thermo-chemical origin.







Discussion of the palaeomagnetic poles and the possible ages of intrusion

According to the previous section, at least two and possibly three remanent magnetic directions have been recorded and detected in the 4 dikes investigated, as summarized in fig. 8 a-e: The Listed direction, the Vigehavn-Bölshavn A direction, and the Vaseaa direction.

It is difficult to decide whether the Bölshavn B direction (333°, -20°) is really different from the Listed direction (307°, -14°) as the B-data are few and selected in a non-radom way from the whole population. In a statistical sense the two directions are different at the 95% significance level, but the Listed direction is clearly the most reliable. In table 3 the mean directions with Fisher's statistics (Fisher 1953) and the corresponding virtual palaeomagnetic pole positions are summarized together with some grouped means.

The values of the magnetic colatitude p show that Bornholm was at a low latitude at the times

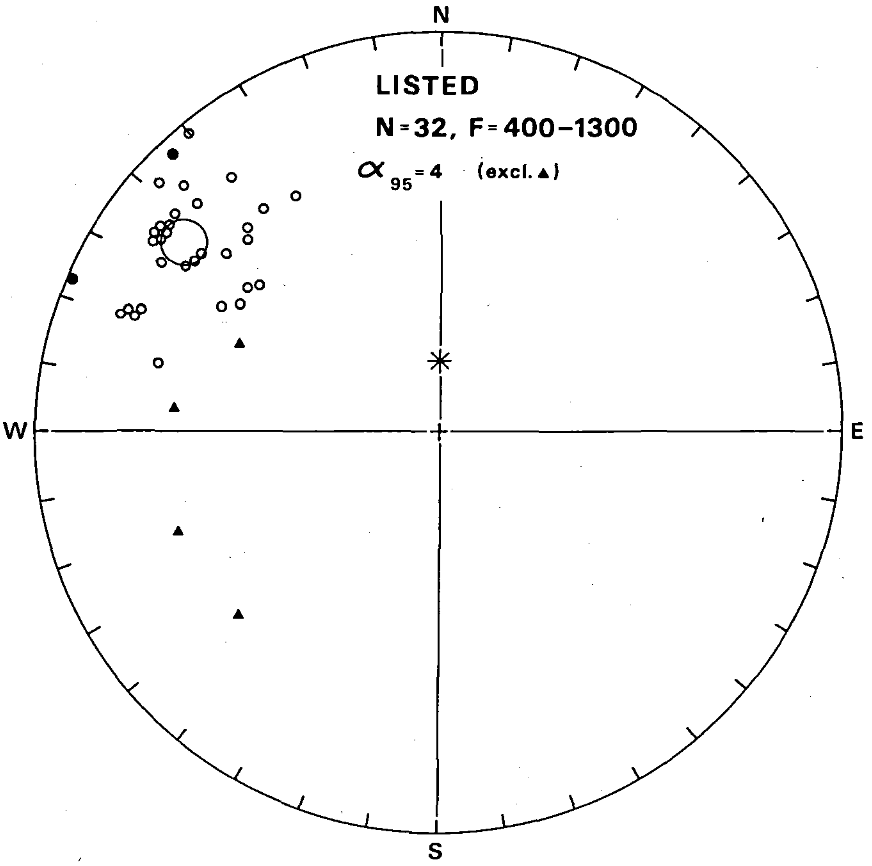


Fig. 8a. Listed dike: Mean direction of cleaned samples (excluding the 4 triangles); asterisk indicates the present Earth's field.

of formation of the dikes, the range of p being 97° to 116°, the corresponding geographical latitude being between 7° and 26°. This infers that tropical or subtropical weathering conditions are likely to have prevailed in the area.

When looking at relevant palaeomagnetic data from the Precambrian and Lower Palaeozoic of Northwestern Europe it must be admitted that the data are still rather limited, and therefore the construction of a reliable apparent polar wander (a.p.w.) path is still open for discussion. In fig. 9 some of the various suggestions of a.p.w. paths are shown, together with the poles from Bornholm with their 95% ovals of confidence.

The a.p.w. path between 1900 and 1300 Myr of Neuvonen (1970, 1973) appears to be rather well established (Larsson 1976), except for the polarity, which is still undetermined, because of a gap in reliable data between 1250 and 900 Myr. Between 900 and 700 Myr a northeastly directed a.p.w. path is most likely, as indicated by the arrow, although details are obscure. Finally, there is a rather large gap between 700 Myr and the Palaeozoic a.p.w. path (Creer 1970), as indicated by the broken curve. Poorter (1975) suggested an a.p.w. curve modified from that of Spall (1973) with a clockwise rotation around 900 Myr (not shown in fig. 9), and recently Poorter (1976 a) published the a.p.w. girdle shown in fig. 9. In the girdle suggested, which is about 20° wide and encloses most of the known poles, allowance is made for statistical errors of pole positions as well as effects due to secular varations and minor excursions of the apparent palaeomagnetic pole. The younger (broken lines)

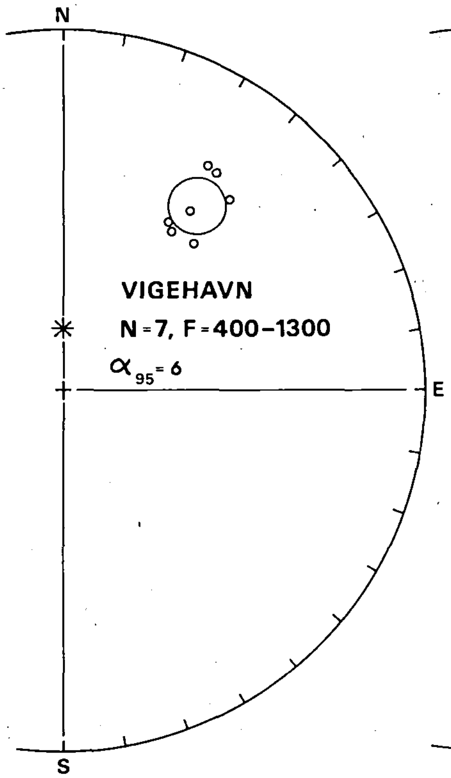


Fig. 8b. Vigehavn dike: Mean direction of cleaned samples.

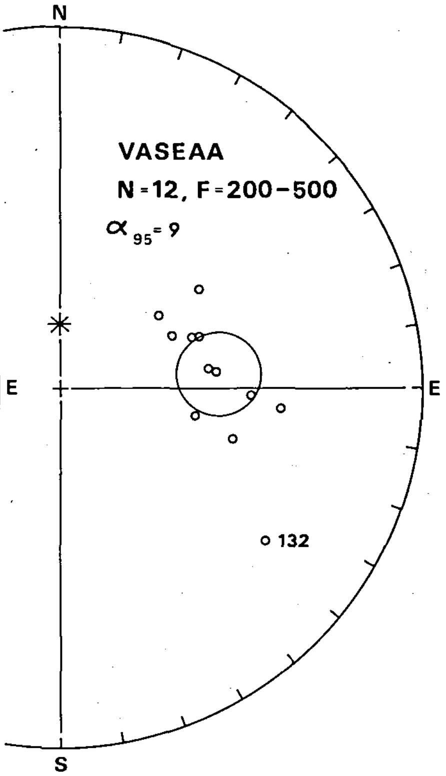


Fig. 8c. Vaseaa dike: Mean direction of cleaned samples.

part of Poorter's girdle, however, does not join the lower Palaeozoic a.p.w. curve of Creer.

If we reverse the sign of the poles defining the a.p.w. path of Neuvonen, we get the dotted curve on the far side of the globe. This solution, although the a.p.w. curve is lengthened somewhat, is preferred for the following reasons. The poles LT (900Myr) and DS (~ 1200 Myr) are closer to the a.p.w. path, and the path conforms with that of Greenville poles of North America with ages 1130–900 Myr (Stewart et al. 1974, Ueno et al. 1975, Morris et al. 1977) following the suggestion that prior to the Caledonian orogeny the Greenvillian and Sveconorwegian areas were close together. As a working hypothesis this solution forthermore has the ad-

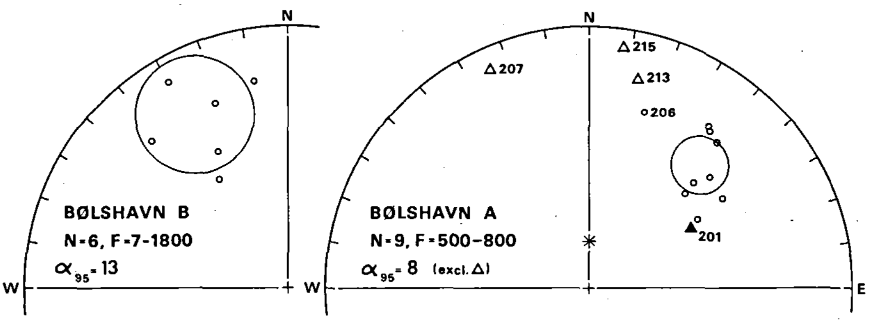


Fig. 8 d. Bölshavn dike: Bölshavn A, mean direction of 9 cleaned samples;Bölshavn B, mean direction of 6 cleaned specimens (cfr. text).

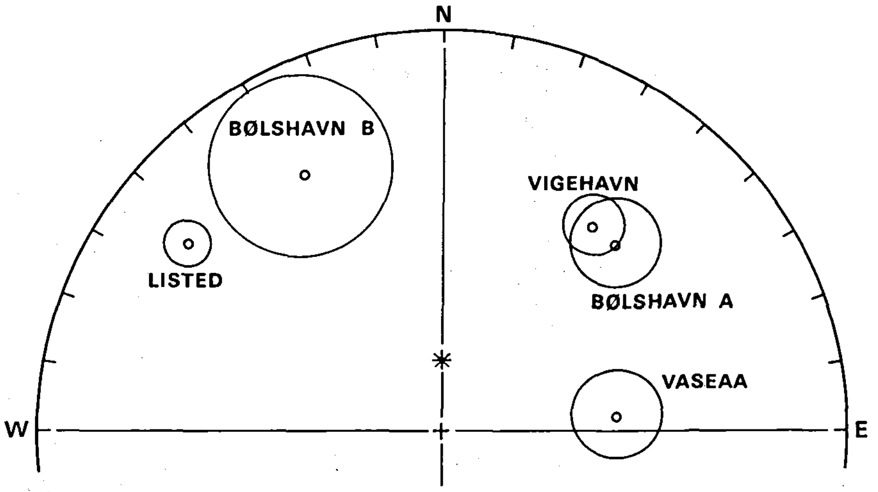


Fig. 8e. Cleaned mean directions with 95% circles of confidence.

vantage that many, more Precambrian palaeomagnetic data are available from North America than from Northern Europe. This hypothesis may thus be more easily tested by future palaeomagnetic work in Precambrian Northern Europe than an a.p.w. curve based entirely on European data.

Turning now to the interpretation of the results from the Bornholm dikes presented here, we note that the magnetic poles 2 and 4 a of the Vigehavn and Bölshavn dikes are close to the crossover of the a.p.w. curve and may thus have an age of either Ordovician-Lower Carboniferous, or middle Precambrian (~ 13–1400 Myr). Objections, however, can be raised against both of these suggestions. Regarding a Lower Palaeozoic age it may be argued that the only traces of igneous activity known from Bornholm during the Palaeozoic (excluding possible dikes cutting the Precambrian basement) are a few thin bentonites known from the Ordovician (Oelandian) shales in the south of Bornholm (some 15–20 km from the sites in question). These bentonites stem from acid volcanic ashes with well developed quartz crystals, so our dikes can hardly be correlated with them.

A possible middle Precambrian age is not very likely for the Vigehavn dike, in that it cuts the

Table 3: Mean directions and apparent palaeomagnetic pole positions.

Site	N(n)	Dm	Im	p	k	α_{95}	R	Pole Position		δp	δm
								lat.	Long.		
1 Listed	32(44)	306.6°	–13.8°	97°	38.9	4.1°	31.2050	13.8°N	250.1°E	2.1°	4.2°
2 Vigehavn	7(14)	35.8	–25.7	104	97.4	6.1	6.9384	15.0°N	158.8°E	3.6	6.6
3 Vaseaa	11(22)	80.6	–44.2	116	27.6	8.9	10.6373	16.0°S	127.8°E	6.3	10.0
4a Bölshavn A	9(35)	42.2	–25.5	103	34.1	8.9	8.7657	12.8°N	152.9°E	5.2	9.6
4b Bölshavn B	(6) *	332.9	–20.1	100	25.5	13.5	5.8045	20.7°N	223.6°E	7.4	14.1
1 + 4b	2(50)	319.5	–17.4	99	19.7	59.7	1.9491	17.7°N	237.3°E	3.2	6.2
2 + 4a	2(49)	39.0	–25.6	103	393.8	12.5	1.9975	14.0°N	155.8°E	7.3	13.5
2 + 3 + 4a	3(71)	50.5	–33.2	108	13.4	35.1	2.8506	5.3°N	147.6°E	23	40

N = number of samples.
n = number of specimens.
Unit weight on N except *).

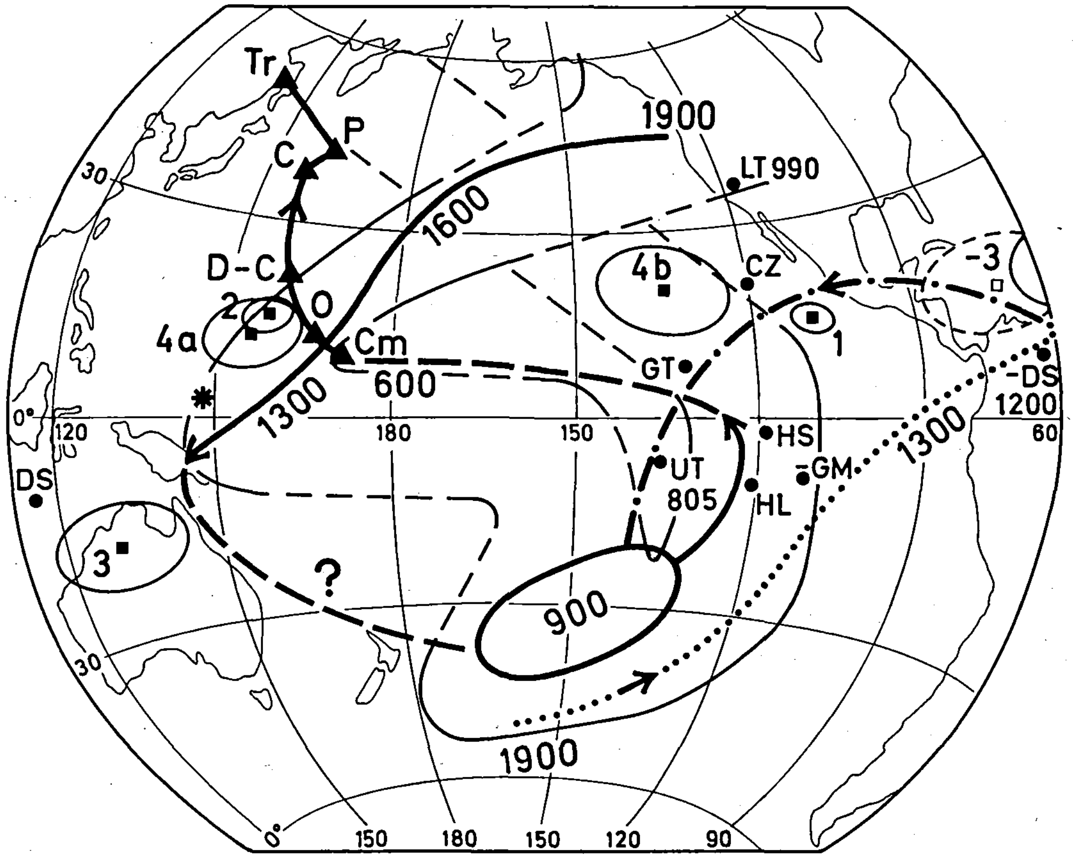


Fig. 9. Apparent polar wander curves and selected palaeomagnetic poles for northwestern Europe according to different authors. The solid curve 1900–1300 Myr is after Neuvonen (1937), 1300–600 Myr is modified after Spall (1973), Paleozoic curve with triangles is after Creer (1970) and girdle after Poorter (1976 a).
The poles of the present work are given with their 95% ovals of confidence (1: Listed, 2: Vigehavn, 3: Vaseaa, 4 a and 4 b: Bölshavn; aterisk: mean of 2, 3 and 4 a). Single poles are: HL (hyperite dike, Sweden, 1573 Myr K/Ar, Mulder 1971), HS (hyperite dike, Sweden, 886 Myr K/Ar, Mulder 1971), DS (dolerites and basalts, Sweden, ~ 1200 Myr K/Ar, Dyrelius 1970), LT & HT (Lower and Upper Torridonian sandstones, Scotland, 990 & 805 Myr Rb/Sr, Irving et al. 1957, Moorbath 1969, Stewart et al. 1973), CZ (Upper Proterozoic – Eocambrian sediments, Czechoslovakia, Bucha 1965), GT & GM (Tillite and Multicolored series, E. Greenland, Upper Precambrian, Bidgood et al. 1961). The dotted a.p.w. curve, as suggested in text, lies on the far side of the globe; it is the mirror curve through the Earth's center of that of Neuvonen, and corresponds to a reversal of polarities before 1200 Myr.

(supposedly) postkinematic Svaneke Granite (being younger than the Hammer Granite of 1390 Myr). It should be mentioned, however, that the younger age of the Svaneke Granite was questioned by Platou (1970), who stated that "it is unknown whether the third deformation observed on East Bornholm in connection with the formation of the Svaneke Granites is of the same age as the deformation observed in connection with the formation of the Hammer Granites".

As previously discussed, the Vaseaa direction may be an intermediate one between that of Vigehavn-Bölshavn A and another one, which could be a reversed Listed direction. Therefore, the initial magnetic age of the Vaseaa dike may well be the same as that of Vigehavn-Bölshavn A or that of the Listed dike, depending on which is the older, despite the large differences in pole positions. Finally, the possibility also exists that the Vaseaa dike was injected as a separate event at around 1200 Myr ago, according to the a.p.w. curves of fig. 9.

If we combine the three poles of Vigehavn, Vaseaa and Bölshavn A (2 + 3 + 4 a in table 3) we get the mean pole position in fig. 9 as indicated with an asterisk; the precision is, however, low (k = 13, α_{95} = 35°) because of the remagnetization suggested above, for which reason this pole position is likely to be better represented by the combined pole (2 + 4 a) of table 3.

The pole of the Listed dike falls 27° from the Bölshavn B pole, ~60° from the reversed Vaseaa pole, and ~ 90° from the Vigehavn-Bölshavn A pole. Thus the Listed direction is certainly of a different age than the Vigehavn-Bölshavn A direction, indicating at least two dike generations.

Comparison with known surrounding poles reveals that the Listed pole is ~20° away from the pole LT of Lower Torridonian (Stoer Group) sandstone in Scotland (990 Myr, Rb/Sr revised age), ~ 33° from the pole UT of Upper Torridonian sandstone (805 Myr, Rb/Sr revised age) and ~ 45° from the pole DS of Jotnian Dolerites and Basalts in Sweden (~ 1200 Myr, K/Ar). The latter pole position is, however, rather uncertain. The distance to two Eocambrian poles GM and GT from East Greenland is ~ 25° (after closing the North Atlantic Ocean according to the 'Bullard fit'), while the distance to CZ is ~10°, where CZ is the pole of late Precambrian rocks from Czechoslovakia (recomputed from table 1 of Bucha (1965) after reversal of sites 4–7). Finally, HL and HS are poles from the Swedish hyperite dolerites with K/Ar ages of 1573 and 886 Myr; they fall between 15° and 25° from the Listed pole, but their metamorphic history is complex and the magnetic pole does not necessarily correspond to the measured K/Ar ages as is discussed by Mulder (1971). The latter author considers the magnetic direction to be the original one (1550 ± 100 Myr); however, the poles fall far away from the Neuvonen a.p.w. curve and fit better with the Sveconorwegian directions. Equivalent rather large discrepancies between the K/Ar-ages (680 Myr) and Rb/Sr-ages (910 ± 35 Myr) have also been found for the late tectonic Bohus Granite in SW-Sweden (Skiöld 1976). A more likely interpretation of the hyperite dolerites may therefore be that the K/Ar ratio as well as the magnetic direction reflect a Sveconorwegian overprint.

Although the data are indeed scattered, it seems reasonable to conclude that the magnetic age of the Listed dike must fall at the beginning or within the range of the poles selected in fig. 9. As an age equal to that of HL can be excluded on geological grounds, a palaeomagnetic estimate may be around 1000 Myr (Post Sveconorwegian or Torridonian age), although an age as young as 800 Myr cannot be quite excluded on the present data.

The palaeomagnetic interpretation of the Bölshavn dike depends on whether the Listed dike is older or younger than the Vigehavn dike. If the Vigehavn dike is middle Precambrian, the Bölshavn A direction is likely to be the original direction, while Bölshavn B is a younger direction, probably induced during moderately elevated temperatures (frictional heating?) when the Listed dike was formed; on the other hand, if the Vigehavn dike is of Lower Palaeozoic age, the Bölshavn B direction is likely to be original, and the dike would then probably be of the same age as the Listed dike.

Conclusions

Taking all available information into consideration the most likely interpretation of the palaeomagnetic results appears to be as follows: Shortly after formation and cooling of the Svaneke Granites (~ 1300 Myr?), injection of the Vaseaa dike may have taken place (equivalent to the Jotnian dikes of Sweden) along NNE striking joints and faults (~ 1200 Myr).

Some 200 Myr later the fault system was reactivated (marginal Sveconorwegian block faulting?), and injection of the Listed and Bölshavn dikes took place. The Vaseaa dike may eventually be of the same age, and later remagnetized. Finally, in Lower to Mid-Palaeozoic time the same fault system was again reactivated, probably as a marginal effect of the Caledonian orogeny, and the Vigehavn dike was intruded. At the same time a severe remagnetization of the Bölshavn dike (A) took place, almost completely masking the original direction (B).

Although at first somewhat confusing, it appears that when fitting the palaeomagnetic data of these 4 minor dikes into the much bigger puzzle of the block faulting history of Bornholm, some of the important geological events have been recorded quite well by the dike 'tape recorder'.

It is hoped that the data presented here may be of further use in combination with future palaeomagnetic and radiometric work. This is indeed needed before a reliable polar wander path, and hence a trustworthy reconstruction of Precambrian palaeogeography for Northwestern Europe, may be obtained.

Acknowledgements. The preparations of samples were made by Bent Nordahl Madsen, drawings by Inge Casten and Torben Riis, all of whom I thank for their collaboration.

Dansk sammendrag

I artiklen beskrives en detailleret palæomagnetisk undersøgelse af 4 diabasgange ved Listed på Bornholm (Listed, Vigehavn, Vaseå og Bölshavn gangene). Ialt 67 orienterede håndprøver blev indsamlet, og heraf blev 137 kerneprøver udboret og undersøgt. Prøverne blev afmagnetiseret trinvist i vekselmagnetfilter op til 1800 Ørsted som vist i fig. 3–7. Middelretningerne af D og I samt α_{95} for det palæomagnetiske felt er fundet til 307°, -14°, 4° for Listed gangen, 36°, -26°, 6° for Vigehavn gangen, og 81°, -44°, 9° for Vaseå gangen, mens for Bölshavn gangen to helt forskellige retninger blev isoleret, Bölshavn A (42°, -25°, 9°) og Bölshavn B (333°, -20°, 13°). Det sidste viser, at der har fundet en remagnetisering af Bölshavn gangen sted længe efter dens oprindelige magnetisering. Vigehavn og Bölshavn A retningen (fig. 8e) er sammenfaldende, hvorfor disses magnetiske alder antagelig er ens; Listed og Bölshavn B retningerne er ligeledes omtrent ens og ca. 90° afvigende fra de førstnævnte og derfor af en ganske anden alder. Vaseå retningen falder nærmest de førstnævntes. men kan evt. være delvist remagnetiseret.

De nævnte stabile remanente magnetiseringsretninger viser, at der er tale om mindst 2 og muligvis 3 generationer af gange af højst forskellig alder. Da palæobredden varierer mellem 7° og 26°, må Bornholm desuden have ligget i tropiske eller subtropiske klimabælter i de pågældende tidsrum.

Ved at sammenligne de tilsvarende virtuelle palæomagnetiske poler med andre data for Nordvesteuropa (fig. 9), viser det sig, at Vigehavngangens samt Bölshavn A retningens poler falder tæt ved den apparente palæomagnetiske polkurves eget skæringspunkt, således at den magnetiske alder kan fortolkes som værende enten omkring ~ 13–1400 mill. år eller ældre palæozoikum.

Da den radiometriske alder (Rb/Sr) af Hammergranitten er 1390 mill. år (Larsen et al. 1976), da Svanekegranitten antages at være yngre end denne, og da Vigehavngangen skærer gennem Svanekegranitten og er finkornet, hvilket indicerer hurtig afkøling, er en så høj magnetisk alder ikke særlig sandsynlig. Der er dog rejst tvivl om (Platou, 1970), hvorvidt Svaneke granitten virkelig er yngre, så en sikker konklusion om, at Vigehavngangen og Bölshavn A retningen er ældre palæozoisk, kan formentlig kun drages, hvis den nævnte tvivl forkastes. Det kan bemærkes, at i Sydsverige kendes nordøststrygende gange af postsilur alder.

Vaseåpolen falder tæt ved 1200 mill. år på den apparente polkurve og kan indicere denne alder for gangen. Helt udelukkes kan det dog ikke, at den remanente retning er intermediær imellem Vigehavnsretningen og en modsat pòlariseret Listedretning. I så fald kan Vaseågangen tillægges samme alder som den af de to grupper, der er ældst (sandsynligvis Listed-polen).

Ser vi endelig på Listedretningen (og Bölshavn B retningen), falder polen herfor i nærheden af de senprækambriske poler for de skotske Torridon sandsten (hhv. 990 og 805 mill. år), nogle remagnetiserede svenske hyperiter (886 mill. år?) samt nogle senprækambriske Tjekkoslovakiske bjergarter. Endelig er forskellen til de to østgrønlandske senprækambriske poler fra den mangefarvede serie og tillitserien efter genlukning af Nordatlanten heller ikke stor.

Selv om data er noget spredte, kan det nok konkluderes, at den magnetiske alder af Listedgangen samt Bölshavn B retningen falder omkring ca. 1000 mill. år, svarende til en postsveconorwegisk eller Torridon alder, selv om en magnetisk alder så ung som ~ 800 mill. år ikke helt kan udelukkes (dog er Listedgangen med sikkerhed ældre end de sandstensgange af formodet eokambrisk alder, der skærer igennem den). Til sammenligning kan endelig nævnes, at en enkelt plagioklas fra Kjeldseågangen 6 km nord for Listedgangen har givet en K/Ar alder på 1000–1100 mill. år (O. Larsen, personlig meddelelse).

Med alle de nævnte forbehold kan det kort resumeres, at vi ved de palæomagnetiske målinger har fået bekræftet Münthers (1945) påvisning af mindst to og muligvis tre gangintrusionsfaser på Østbornholm: 1. Vaseågangen ~ 1200 mill. år (som den mest usikre), 2. Listedgangen (med Bölshavn B magnetiseringen) på antagelig ca. 1000 mill. år, samt 3. Vigehavngangen (ældre til midt-palæozoisk (postsilur?)), ved hvilken lejlighed Bölshavngangen er blevet remagnetiseret til Bölshavn A retningen.

På basis af de kendte data i fig. 9 samt en parallelisering med de palæomagnetiske poler for Greenville provinsen (900–1130 mill. år) i Nordamerika, foreslås endelig, at den ældre del af den europæiske apparente polvandringskurve skal spejlvendes, svarende til en reversion af de ældre poler, som vist i fig. 9 med prikket kurve på jordklodens bagside.

References

Abrahamsen, N. 1973: Magnetic secular variation in Denmark, 1500–1970. *J. Geomag. Geoelectr.* 25: 105–111.

Abrahamsen, N. 1974: Palaeomagnetic age of the WNW-striking dikes around Gothenburg, Sweden. *Geol. Fören. Stockholm Förh.* 96: 163–170.

Beckmann, G. E. J. 1976: A palaeomagnetic study of part of the Lewisian complex, North-west Scotland. *J. geol. Soc. London* 132: 45–59.

Bidgood, D. E. T. & Harland, W. B. 1961: Palaeomagnetism in some East Greenland sedimentary rocks. *Nature* 187: 633–634.

Briden, J. C. 1976: Application of palaeomagnetism to Proterozoic tectonics. *Phil. Trans. roy. Soc. London* A 280: 405–416.

Bruun-Petersen, J. 1975: Origin and correlation of the sandstone dykes at Listed, Bornholm (Denmark). *Bull. geol. Soc. Denmark* 24: 33–44.

Bucha, V. 1965: Results of the palaeomagnetic research on rocks of Precambrian and Lower Palaeozoic age in Czechoslvakia. *J. Geomagn. Geoelectr.* 17: 435–444.

Bullard, E. C., Everett, J. E. & Smith, A. G. 1965: The fit of the continents around the Atlantic. *Phil. Trans. roy. Soc. London* A 258: 41–51.

Bylund, G. 1974: Palaeomagnetism of dykes along the southern margin of the Baltic Shield. *Geol. Fören. Stockholm Förh.* 96: 231–235.

Callisen, K. 1934: Das Grundgebirge von Bornholm. *Danmarks geol. Unders.* (2) 50: 266 pp.

Creer, K. M. 1970: A review of palaeomagnetism. *Earth Science Reviews* 6: 369–466.

Dyrelius, D. 1970: Preliminary paleomagnetic investigation of dolerites and basalts in Dalarne, Sweden. *In:* Runcorn, S. K. (ed.) *Paleogeophysics* 243–246, Academic Press.

Fisher, R. 1953: Dispersion on a sphere. *Proc. roy. Soc. London* A217: 295–305.

Giddings, J. W. & McElhinny, M. W. 1976: A new index of palaeomagnetic stability for magnetite bearing igneous rocks. *Geophys. J. roy. astr. Soc.* 44: 239–251.

Grönwall, K. A. & Milthers, V. 1916: Kortbladet Bornholm. *Danmarks geol. Unders.* (1) 13: 281 pp.

Irving, E. 1964: *Palaeomagnetism.* London: Wiley. 399 p.

Irving, E. & Runcorn, S. K. 1957: Analysis of the palaeomagnetism of the Torridonian sandstone series of Northwest Scotland.*Phil. Tran. roy. Soc. London* A 250: 83–99.

Irving, E. & McGlynn, I. C. 1976: Proterozoic magnetostratigraphy and the tectonic evolution of Laurentia. *Phil. Trans. roy. Soc. London* A 280: 433–468.

Jaeger, J. C. 1968: Cooling and solidification of igneous rocks. *In:* H. H. Hess & A. Poldervaart (eds.): *Basalts* 2: 504–536.Interscience Publs.

Jensen, Å. 1966: Mineralogical variations across two dolerite dykes from Bornholm. *Meddr dansk geol. Foren.* 16: 369–455.

Jensen, Å. 1968: Opaque minerals in the Precambrian plutonic rocks of Bornholm and their relation to the development of these rocks. *Meddr dansk geol. Foren.* 18: 79–96.

Klingspor, I. 1976: Radiometric age-determination of basalts, dolerites and related syenites in Skåne, Southern Sweden. *Geol. Fören. stockholm Förh.* 98: 195–216.

Larsen, O. & Springer, N. 1976: Radiometrisk datering af granitoider i Blekinge og på Bornholm. *12th Nordic Geol. Meeting in Gothenburg (abstracts).*

Larsson, S. Å. & Magnusson, K.-Å. 1976: The magnetic and chemical character of Fe-Ti oxides in the Ulvö dolerite, Central Sweden. *Sveriges geol. Unders.* (C) 723: 29 pp.

Micheelsen, H. 1961: Bornholms grundfjeld. *Meddr dansk geol. Foren.* 14: 308–349.

Milthers, V. 1930: Bornholms geologi. *Danmarks geol. Unders.* (5) 1: 140 pp.

Moorbath, S. 1969: Evidence for the age of deposition of the Torridonian sediments of Northwest Scotland. *Scottish J. Geol.* 5: 154–170.

Morris, W. A. & Roy, J. L. 1977: Discovery of the Hadrynian Polar Track and further study of the Greenville problem. *Nature* 266: 689–692.

Mulder, F. G. 1971: Palaeomagnetic research in some parts of central and southern Sweden. *Sveriges geol. Unders.* (C) 653: 56 pp.

Münther, V. 1945: Sprækkedale og diabasintrusioner på Bornholm. *Meddr dansk geol. Foren.* 10: 641–645.

Münther, V. 1957: Grænsen mellem granitten og Nexøsandstenen belyst gennem magnetiske målinger. *Meddr dansk geol. Foren.* 13: 254–255.

Münther, V. 1973: Dominerende forkastningszoner på Bornholm baseret på anomalier af den vertikale magnetiske intensitet. *Danmarks geol. Unders.* (2) 85: 161 pp.

Neuvonen, K. J. 1970: Palaeomagnetism of the dike systems in Finland V. *Bull. geol. Soc. Finland* 42: 101–107.

Neuvonen, K. J. 1973: Remanent magnetization of the Jotnian sandstone in Satakunta, SW-Finland. *Bull. geol. Soc. Finland* 45: 23–27.

Neuvonen, K. J. 1974: Palaeolattitude and cause of the Svecokarelian orogeny. *Bull. geol. Soc. Finland* 46: 75–79.

Pauly, H. 1944: Blygangen ved Spidlegaard. *Meddr dansk geol. Foren.* 10: 468–473.

Piper, J. D. A. 1976: Paleomagnetic evidence for a proterozoic super-continent. *Phil. Trans. roy. Soc. London* A 280: 469–490.

Platou, S. W. 1970: The Svaneke Granite Complex and the gneisses on East Bornholm. *Bull. geol. Soc. Denmark* 20: 93–133.

Poorter, R. P. E. 1975: Palaeomagnetism of Precambrian rocks from Southeast Norway and South Sweden. *Phys. Earth Planetary Interiors* 10: 74–87.

Poorter, R. P. E. 1976a: Palaeomagnetism of Precambrian rocks from Norway and Sweden. Thesis, Utrecht.

Poorter, R. P. E. 1976b: Palaeomagnetism of the Svecofennian Lofthammargabbro and Jotnian dolerites in the Swedish part of the Baltic Shield. *Phys. Earth Planetary Interiors* 12: 51–64.

Rasmussen, H. W. 1966: *Danmarks geologi.* København: Gjellerup. 174 pp.

Saxov, S. 1959: Listed diabas dike, density and gravity. *Meddr dansk geol. Foren.* 14: 133–140.

Schönemann, A. 1972: *Magnetiske undersøgelser af nogle diabas-gange på Bornholm.* Unpublished thesis, University of Copenhagen.

Skiöld, T. 1976: The interpretation of the Rb-Sr and K-Ar ages of late Precambrian rocks in south-western Sweden. *Geol. Förh.* 98: 3–29.

Spall, H. 1973: Review of Precambrian palaeomagnetic data for Europe. *Earth and Planetary Sci. Letters* 18: 1–8.

Stacey, F. D. & Banerjee, S. K. 1974: *The physical principles of rock magnetism.* Amsterdam: Elsevier. 195 pp.

Stewart, A. D. & Irving, E. 1974: Palaeomagnetism of Precambrian sedimentary rocks from NW Scotland and the Apparent Polar Wandering Path of Laurentia. *Geophys. J. roy. astr. Soc.* 37: 51–72.

Ueno, H., Irving, E. & McNutt, R. H. 1975: Palaeomagnetism of the Whitestone Anorthosite and Diorite, the Greenville Polar Track, and relative motions of the Laurentian and Baltic Shields. *Can. J. Earth Sci.* 12: 209–226.

Ussing, N. V. 1899: Sandstensgange i granit på Bornholm. *Danmarks geol. Unders.* (2) 10: 87–100.

Welin, E. & Blomqvist, G. 1966: Further age measurements on radioactive minerals from Sweden. *Geol. Fören. Stockholm Förh.* 88: 3–18.

Wright, A. E. 1969: Precambrian rocks of England, Wales and Southeast Ireland. *Mem. Am. Assoc. Petrol. Geol.* 12: 93.

Sedimentary history of the island Læsø, Denmark

JENS MORTEN HANSEN

Hansen, J. M.: Sedimentary history of the island Læsø, Denmark. *Bull. geol. Soc. Denmark*, vol. 26, pp. 217–236. Copenhagen, December 2nd 1977.

Coastal sections on the island Læsø in the northern Kattegat, Denmark, expose many well-preserved sedimentary structures. These structures have been studied in order to gain information about the postglacial sedimentary history of the island. Furthermore, numerous beach ridges make it possible to reconstruct the size and shape of the island at all stages of its development. During early postglacial transgressions and alternating regressions the island was represented by a shoal. During the transgressions the shoal was inhabited by the heart urchin *Echinocardium cordatum*, whereas it was inhabited by the lugworm *Arenicola marina* during regressions. Heart urchin-burrowed layers are found in three horizons with lugworm-burrowed beds below and above the upper heart urchin-burrowed horizon. The burrows of the two animals are found in different sedimentary facies, thus also suggesting different hydrographic conditions by means of physical sedimentary structures. In places the lugworm-burrowed horizons are characterized by irregular erosion surfaces. Similar structures are found today at the pseudo-tidal flats south of Læsø, where they are formed by partial erosion of algal mats. The alternation of different sedimentary structures including trace fossils and irregular erosion surfaces is thus believed to reflect postglacial transgressions and regressions.

Jens Morten Hansen, Henningsens Allé 2, DK–2900 Hellerup, Denmark. August 10th, 1977.

The island Læsø in the northern Kattegat, Denmark, was built up mainly during postglacial transgressions and regressions. The sea cliffs provide extensive sections of sedimentary structures including well-preserved trace fossils. Numerous beach ridges make it possible to reconstruct size and shape of the island at all stages of its development (fig. 1). The combined evidence from beach ridges and other sedimentary structures provides a detailed history of the forces and events involved. The cliff at Bansten Bakke (fig. 2), which cuts through an old tongue of land, shows a continuous sequence of sediments from the initial transgressions as far as the maximum extent of series of Subboreal transgressions. In addition, a study of the recent

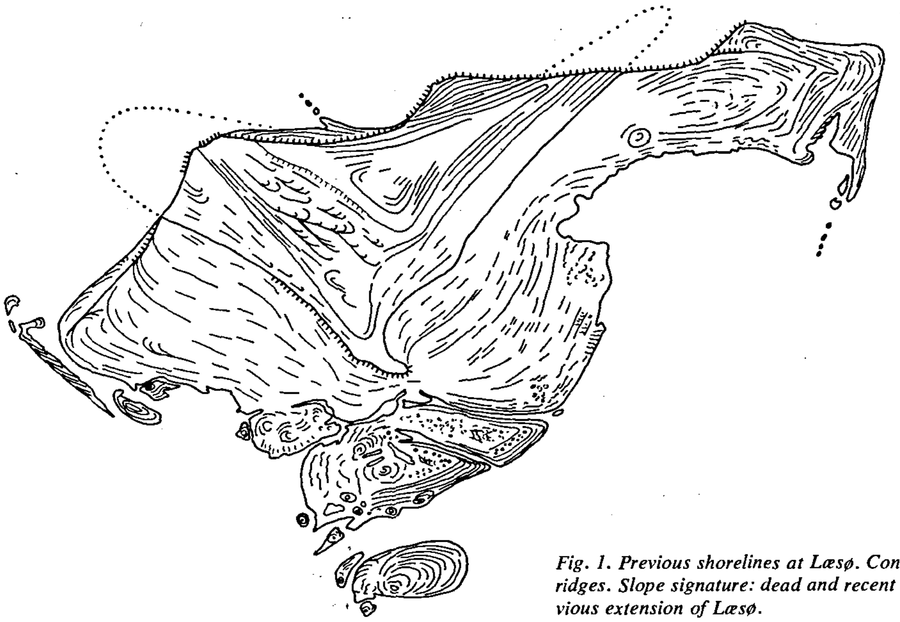


Fig. 1. Previous shorelines at Læsø. Continuous lines: beach ridges. Slope signature: dead and recent cliffs. Stippled: previous extension of Læsø.

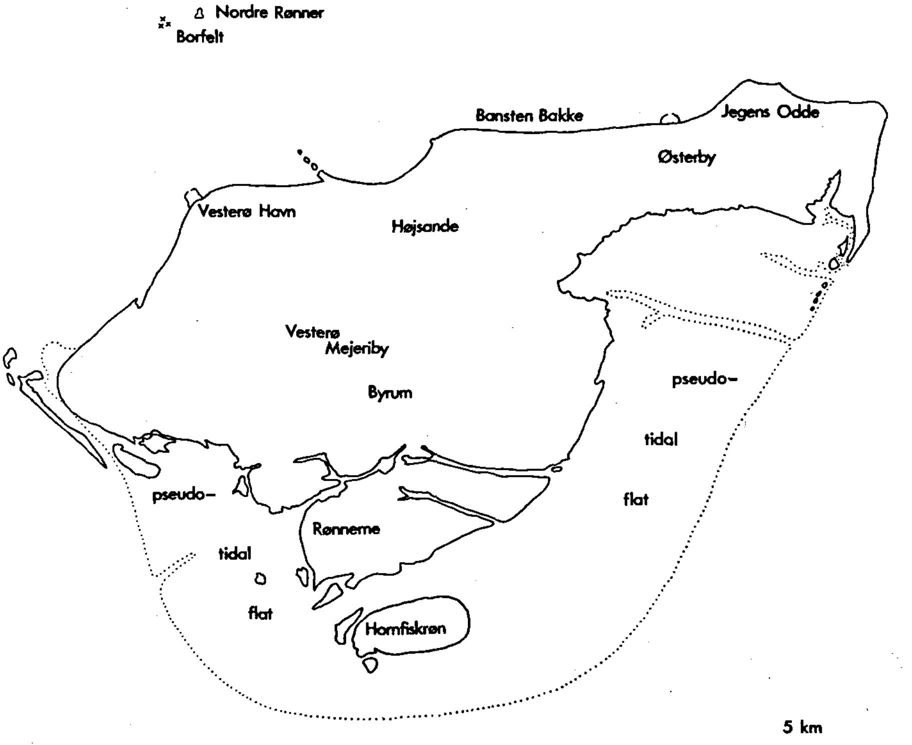


Fig. 2. Locality map.

pseudo-tidal flats south of Læsø provides an explanation of some of the structures involved and adds significantly to the conclusions that can be drawn.

Previous work has been carried out by Jessen (1897, 1920 & 1936), who gave an outline of the general geology. Michelsen (1967) dealt with the Foraminifera from the late glacial Yoldia Clay and from the lowermost part of the sand and gave (1968) a brief outline of the beach ridge sytem. Mörner (1969) visited the island as a part of a major work on the late and postglacial history of the Kattegat.

The island is built up of 5 sedimentary units (mentioned in sedimentary order):

1. The *Yoldia Clay*. Exposed north of Vestrø Havn, at Bansten Bakke and in several clay pits in the southern part of the island. Thickness unknown. Radiocarbon age: 10.960 ± 180 years BC (Tauber 1966).
2. *Residual gravel and blocks* resting on the Yoldia Clay. Thickness 0–0.5 m.
3. *Marine sand*. Exposed in the coastal sections along the north and west coast and in a pit 3 km west of Byrum. Thickness 0–13 m.
4. *Beach sediment*. Exposed in the coastal sections along the north and west coast and in several pits. Thickness 0–5 m. Radiocarbon age: Tooth of sperm whale (*Physeter catodon*) found north of Byrum, 4.5 m above sea level, 980 ± 80 years BC (Tauber, in litt.).
5. *Aeolian sand*. Thickness 0–17 m. Main part formed in the 18th century.

The present paper deals with the Yoldia Clay, laying special emphasis on the overlaying marine sand and beach sediments, which contain the well-preserved sediment structures.

The Yoldia Clay

The late glacial Yoldia Clay underlies the entire northern Kattegat sea and covers extensive parts of northern Jylland, and forms the platform upon which the postglacial sand of Læsø has been

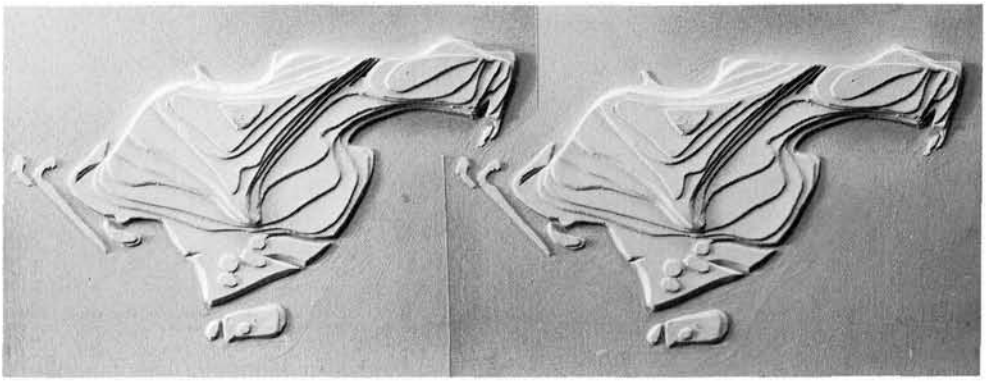


Fig. 3. Model (stereopair) showing the supposed relation between time and shape of Læsø. Each step roughly *corresponds to 500 years. Notice that the steps do not correspond to contours, since the isostatic recovery of the northern part of Læsø has been 2–3 m greater than of the southern part (cf. Mertz 1924).*

built up. It has a variable lithology, ranging from sticky, silty clay to more or less sandy silt or even to muddy and stony sand. In places the Yoldia Clay is very rich in stones and boulders some of which are very large (about 50 tons). In the southern part of Læsø, where the postglacial sand sheet is very thin, these boulders are strewn over considerable areas, probably as a result of outwash during the Ancylus time and during the postglacial transgressions (Michelsen 1967). Jessen (1897) suggested that the boulders were derived from drift ice, an idea that might be supported by the fact that the Yoldia Clay is specifically rich in boulders where it formed highs at the sea bottom. The small islands and shoals north of Læsø (Nordre Rønner and Borfelt) are almost entirely built up of boulders of quite unusual size in spite of the total lack of tills or till-ridges on Læsø and its neighbourhood. Therefore it seems likely that the Yoldia Clay was formed as some kind of drop-till while the late Weichselian ice stood near the Swedish west coast or even farther westwards. Mörner (1969) assumed the presence of a till-ridge running north-south through Læsø. The presence of this till-ridge is speculative and not supported by primary observations. If present, the till-ridge must be buried under several metres of Yoldia Clay.

Locally the Yoldia Clay contains an abundant fauna dominated by *Saxicava arctica, Macoma calcarea* and *Balanus* sp., whereas *Portlandia arctica* is rare. However, fossils are generally few and those that occur are often crushed, probably by boulders as they hit and deformed the sediment or by ice bergs ploughing through the sediment. Both in borings and exposures the Yoldia Clay is overlain by a thin layer of gravel and stones obviously derived from the clay. This layer is equivalent to the boulders strewn on the southern part of Læsø.

The postglacial sand

Briefly the postglacial sand can be divided into an older and a younger part with reference to topography. The older part forms the triangular raised part of the island, which to the south is surrounded by the younger part, and to the north by the sea. The two parts of different age are separated by fossil cliffs and big beach ridges. The older part of the sand formation is up to 13 m thick and elevated 6 to 11 m above sea level, whereas the younger part is much thinner, ranging mostly from 0 to 3 m, and is not elevated more than 4.5 m above sea level. During earlier stages Læsø had a shape much like that of the island Anholt in the middle of the Kattegat. As seen in figs. 1 & 3, the eastern end of this older part of Læsø is cut by the present shoreline. The section at this locality shows the previous exist-

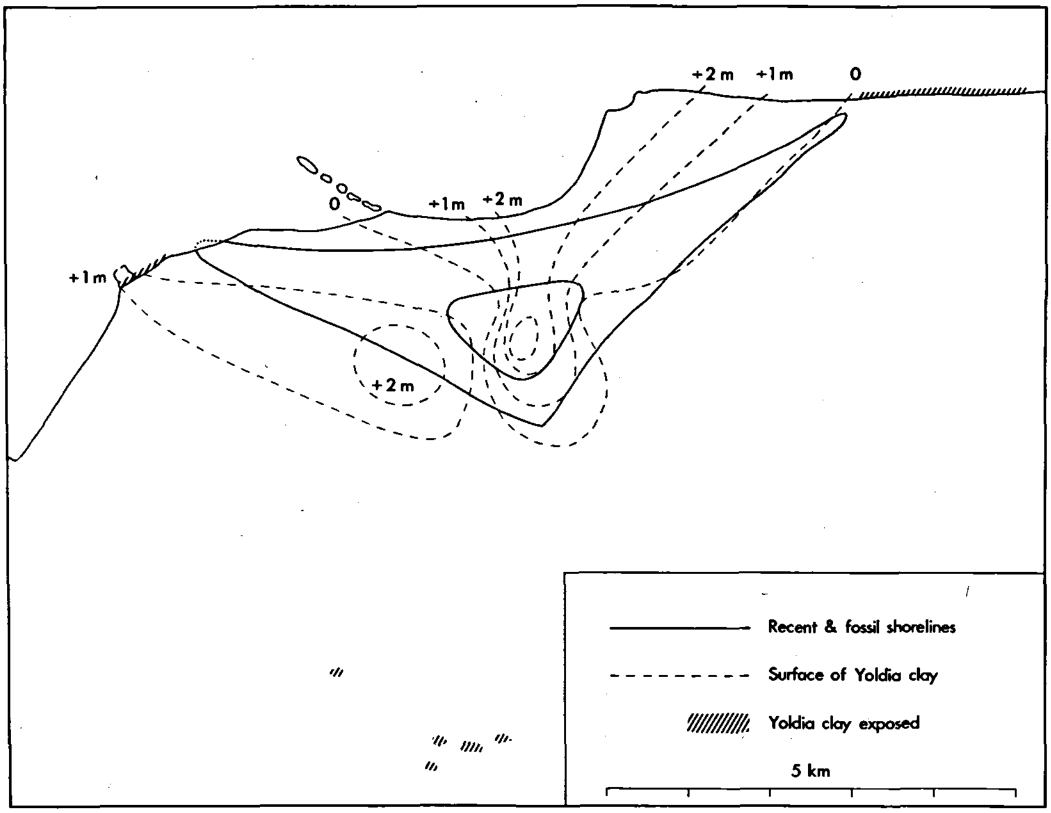


Fig. 4. Surface of the Yoldia Clay and early stages of Læsø's development.

ence of a tongue of land very like the eastern part of Anholt and orientated in the same direction.

The island of Anholt is built up on the lee side of a moraine knoll (Jessen 1897 & Schou 1945). However, no such structure exists or has existed at Læsø. On the contrary, Læsø seems initially to have been built up on the lee side of a high but submerged part of the Yoldia Clay (fig. 4). The triangular "core" of Læsø from which point growth started, is situated immediately east of the highest part of the Yoldia Clay under the sand. From this point Læsø grew northeastwards forming a long tongue of land according to the dominating wind direction, and also west- and southwards in response to the position of the Yoldia Clay platform. As seen in fig. 1 this growth took the form of a succession of recurved spits on the SW side of the island. These recurved spits migrated southeastwards. In contrast, the growth of the tongue of land followed a series of linear beach ridges.

During a postglacial transgression maximum, probably a Subboreal transgression (Iversen 1937 & 1967) (see discussion later), the fossil cliffs and big linear beach ridges surrounding the older triangular part of Læsø were formed. Subsequent shallowing of the sea produced a new regime of currents around Læsø. This is evident from the fact that the recurved spits on the southwestern part of Læsø during these stages migrated northwestwards, whereas they migrated southeastwards during the older stages (cf. fig. 1). It is clear that the sea shallowed considerably after the Subboreal transgression because of the fact that the marine sand surrounding the old triangle is only elevated maximally 4.5 m above present sea level, whereas the old triangle is elevated at least 6 m, except for a very narrow

Fig. 5. Irregular erosion of algal mat; pseudo-tidal flat southwest of Læsø. Notice that the surface is scattered with traces after Corophium volutator.

zone between the old and the young part. By this process the Yoldia Clay platform came so close to the sea level that the wave action at the south coast became of less influence, resulting in a shape completely different from the old triangle.

In addition, the large, younger peninsula on which the village of Østerby is situated was initiated by the occurrence of an island east of the older triangular island. The two islands became probably interconnected by a bar running from the area north of Bansten Bakke to Jegens Odde, where a cliff section shows sedimentary structures including trace fossils similar to those in the cliff at Bansten Bakke.

The southernmost part of Læsø has been formed in a rather different way. The beach ridges are very irregular and low. Here the surface of the Yoldia Clay is very close to the sea level, thus strongly controlling the shoreline, even when minor changes in sea level arise. The area is believed to have been formed by emergence and overgrowth of a pseudo-tidal flat rather similar to that found south of Læsø today. The southern part of Læsø, Rønnerne, is cut by numerous pseudo-tidal channels carrying the water in and out, when the area occasionally is partly submerged. The lower part of the area between the pseudo-tidal channels is covered by halophytes alternating with numerous very shallow ponds. The salt concentration in the pond water varies greatly. During rainy days the water may be nearly fresh, while on hot sunny days the salinity greatly exceeds that of the sea water. The faunal and floral elements in the ponds and the channels are thus restricted to a few species of arthropods and algae. The higher part of the area between the pseudo-tidal channels is dominated by ericaceans.

The topography of channels and ponds at the southernmost part of Læsø has mostly been produced by the emergence of the pseudo-tidal flat through the formation of many small islands that steadily grew by accretion of plant-remains and sand at the borderlines of the islands. Thus the islands as seen from the air (e.g. Hornfiskerøn) somewhat resemble mussel shells with their numerous growthlines.

Pseudo-tidal flats

In the ultimate stages of the history of Læsø the Yoldia Clay platform was raised so much, that on the southern part of Læsø it became very close to the sea level. In this way a wave-cut platform, which soon developed into a pseudo-tidal flat, was formed. In most places the pseudo-tidal flat extends 5 km or more south of Læsø (fig. 2). It should be emphasized that the onshore and offshore currents of seawater on this pseudo-tidal flat are not controlled by normal tidal forces, but rather by wind strength and direction. Thus the flat can be exposed to the air for considerable periods, e.g. a month, and submerged for even longer periods. However, these alternating periods of different hydrographic conditions usually change after a few days, so that the sand only very rarely becomes completely dry.

The sedimentation in this area seems to be partly controlled by algal mats, which cover the entire area. Therefore sedimentary structures other than horizontal lamination and, less common, small scale ripples are rare. The algal mats are usually 1–2 cm thick and not very cohesive. They can be eroded by the pseudo-tidal flow of water to produce irregular erosional surfaces (fig. 5). The structure of these surfaces is treated later. During strong gales the wind may cause erosion of the algal mats because of drying. This has only been observed by the author once (from an aeroplane), but on that occasion an area of about 30 km^2 was covered with numerous small barcan-like aeolian dunes, not more than 1 m high. The dunes were destroyed by the next in-

Fig. 6. Paddling trails of the seagulls Larus argentatus *or* L. fuscus. *The surface is scattered with traces after* Corophium volutator.

cursion of the sea. During such gales stony deflation surfaces can also be formed. At the flats southwest of Læsø, where the sand in places is rather stony because of outwash from the Yoldia Clay, such deflation surfaces are frequent. The pebbles are usually covered and bound together by a peculiar alga, which forms thin parchment-like and very stony sheets, thus stabilizing the deflation surface for considerable periods of time.

Because of these extreme conditions the diversity of the fauna is rather limited. The main constituents are *Arenicola marina, Nereis diversicolor, Corophium volutator* and *Cardium edule*, which all are burrowing animals. In addition rather small amounts of other molluscs are present, e.g. *Mya arenarea*, which also burrows, and a few epifaunal elements dominated by *Littorina littorea* and *Hydrobia ulvae*. The distribution of these animals is somewhat patchy, the lower part of the pseudo-tidal flat being dominated by *Cardium edule*, the upper part by *Arenicola marina*. Small, very shallow depressions, which are not completely dried out during temporary periods of exposure, are dominated by *Corophium volutator*. It is a general rule that the burrowing depth of the animals roughly corresponds to the number of days in which the sand is exposed during a year.

Otherwise the area is inhabited by a great number of birds, which are not without importance for the sand-accumulation.Seagulls are very common in the area and largely feed upon animals from the upper part of the sediment using a special method. With their heads turned into the wind the seagulls 'paddle' rapidly with both legs, thus whirling up the sediment containing their food. Moving foreward against the wind a peculiar kind of trace is formed (fig. 6), which I suggest calling a 'paddling trail'. Hertweck

Fig. 7. Central part of the cliff at Bansten Bakke showing the upper (a) and the middle (b) Echinocardium-*burrowed horizon intercallated with sediment of facies 1. In the middle* Echinocardium-*burrowed horizon (b), the primary sedimentary structures are totally obscured in two minor horizons, whereas horizontal lamination is partly visible outside these horizons.*

Fig. 8. Beach sediment from the eastern part of the cliff at Bansten Bakke. Stone-layers dipping southeastwards intercallated with parallel laminted and convex upwards cross-bedded sand-ripples migrating northwestwards.

(1970: 110) called this kind of trail a resting trace. However, this description is considered to be inaccurate, since the paddling trails can be very long (30 m or more), and since this special paddling behavior in seagulls has been observed several times. Furthermore, the paddling trails are preferentially found in the shallow depressions where *C. volutator* predominates. The paddling trail is composed of two parallel rows of U-shaped furrows in the sand, with the open end of the U in the direction of movement. The paddling trail leaves the sand completely loose with most of the algal filamants on the top of it. If the sea-water begins to move before the sand is reinhabited and bound by the algae, the paddling trails will form week points in the algal mat where erosion can start and undermine the mat, which is then easily broken down.

Sedimentary structures

The cliff at Bansten Bakke (figs. 7, 8 & 9), which cuts through an old tongue of land, shows many extremely well-preserved structures, both trace fossils and physical sedimentary structures.

In general the cliff shows the Yoldia Clay at the bottom, overlain by three horizons intensively bioturbated by *Echinocardium cordatum*. These horizons are generally horizonatally laminated or small-scale ripple laminated. The *Echinocardium*-burrowed horizons are interbedded with large-scale cross-laminated or small-scale rippled horizons. In the latter type of sediment the dominating trace fossils are funnels made by *Arenicola marina*. It is remarkable that where the two types of trace fossils are found together, their cross-cutting relationships nevertheless indicate that the two species never inhabited the sediment together: either all *Arenicola* funnels are cut by *Echinocardium* burrows or the *Echinocardium* burrows are cut by *Arenicola* funnels (fig. 10).

In the upper part of the cliff section other structures are encountered. These are very irregular erosional surfaces, which are believed to have been formed by partial erosion of algal mats (see below), and a deflation surface represented by a single layer of partly polished stones.

To the east the section is capped by beach ridges composed of very coarse-grained layers interbedded with cross-laminated sand. The entire section is overlain by aeolian sand, in places developed as small dunes with large-scale low-angle concave upwards cross-laminations.

Physical sedimentary structures

On the basis of physical sedimentary structures alone three major sedimentary facies can be distinguished. These are:

Facies 1: Figs 7, 9, 10, 15, 17, 18 & 20. Large-scale cross-laminated horizons (of which there are four) with rather few trace fossils preserved. These trace fossils are dominated by funnels made by *Arenicola marina*. The large-scale cross-laminations are mostly of two kinds: 1) erosive structures composed of either planar or concave upwards sets and 2) nonerosive planar to convex upwards sets. The convex upwards sets are quite similar to those described under facies 3. The structures of facies 1 commonly are associated, especially in the upper and middle horizons, with irregular erosion surfaces. The uppermost horizon of this type contains a deflation surface, whereas the lowermost horizon

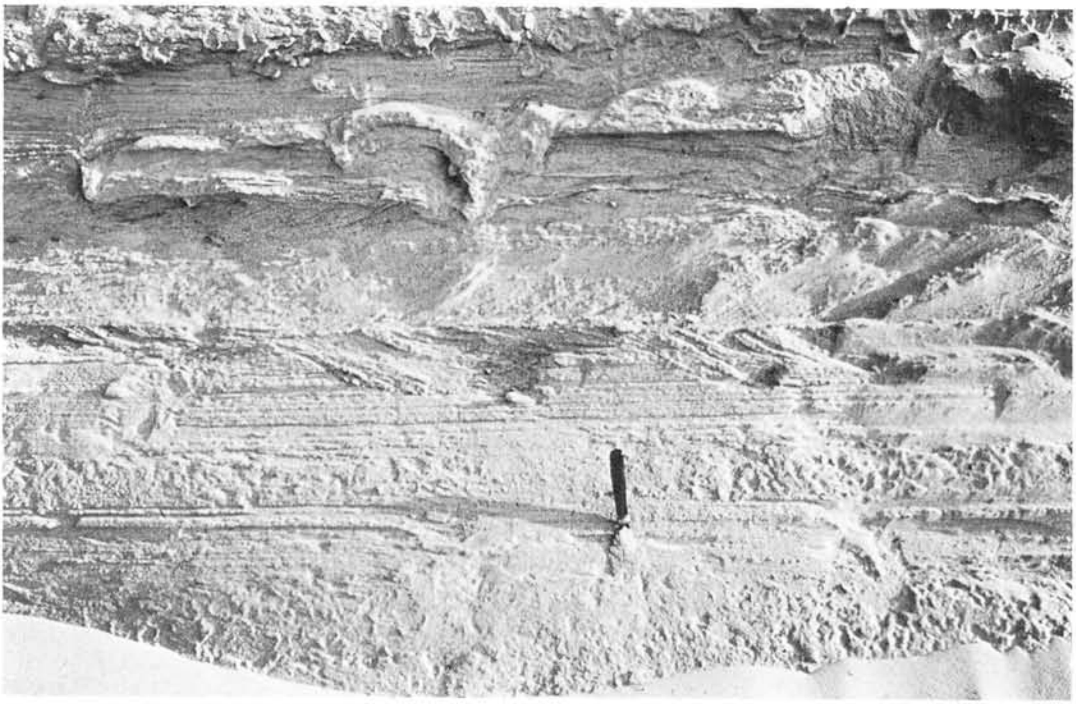


Fig. 9. Central part of the cliff at Bansten Bakke showing sediment of facies 2 containing Echinocardium *burrows and irregularly eroded by sediment of facies 1 containing* Arenicola *funnels.*

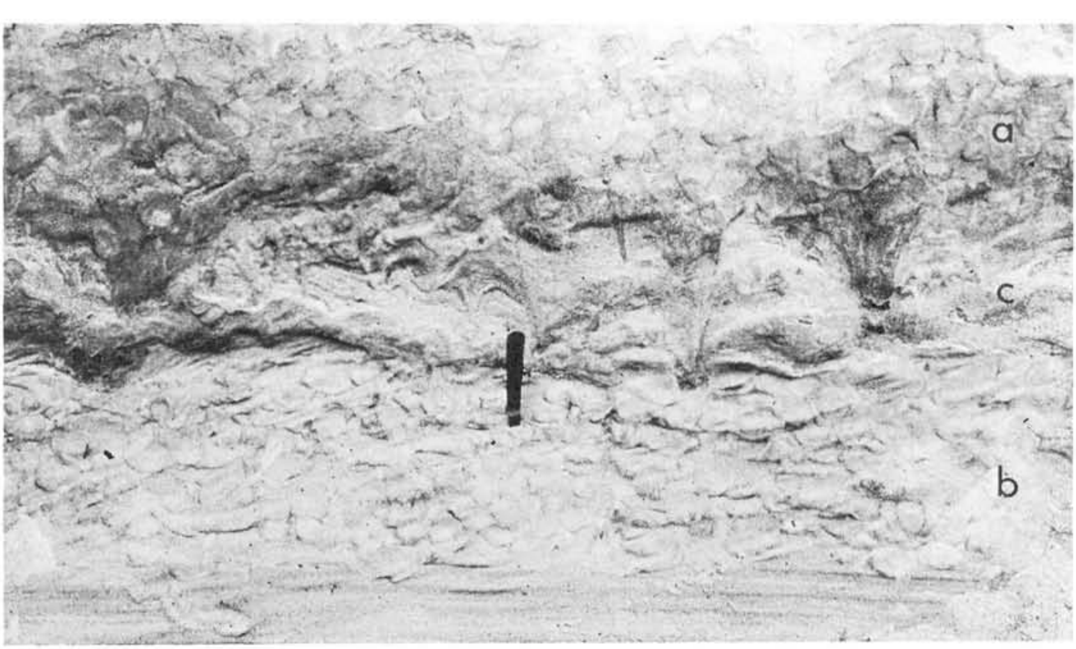


Fig. 10. Echinocardium *burrows from the upper (a) and middle (b)* Echinocardium*-burrowed horizon separated by a thin horizon of facies 1 containing* Arenicola *funnels (c). All the* Arenicola *funnels are truncated by* Echinocardium *burrows from horizon a, while the* Arenicola *funnels cut the* Echinocardium *burrows from horizon b indicating that the two species did not live in the sediment simultaneously. Furthermore,* Echinocardium *burrows from horizon a are found to a depth of c. 10 cm below the upper limit of the* Arenicola *funnels indicating that the burrowing depth of* Echinocardium *could be at least 10 cm.*

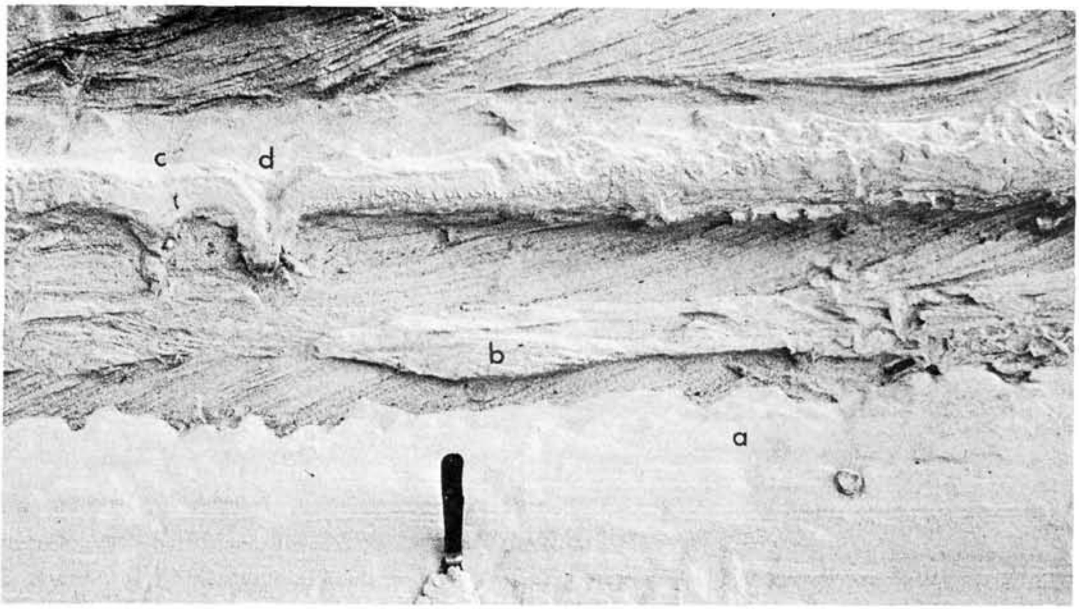


Fig. 11. Sediment of facies 2 (a) without Echinocardium *burrows irregularly eroded by sediment of facies 1 (b) containing* Arenicola *funnels (c, d) cut both laterally and centrally by the cliff-section.*

contains no such structures that would indicate very shallow water or exposure to the air. In addition the lowermost horizon contains numerous horizontally laminated layers. The orientation of the cross-laminations seems to be bimodal to polymodal, which in places gives rise to well developed 'herringbone' structures.

Facies 2: Figs 7, 9, 10, 11, 14, 15, 16, 17 & 20. Horizons (of which there are three) with small-scale troughs, small-scale ripple lamination and horizontally laminated layers. This type of sediment is associated with numerous burrows of *Echinocardium cordatum* that in many places completely have obscured the physical sedimentary structures. The orientation of the small-scale ripples seems to be random.

Facies 3: Fig. 8. In this facies there are three basic structures: 1) 10–100 cm thick, gently SE dipping layers composed of very stony horizons and parallel to them, parallel-laminated sand, 2) scour and fill structures, and 3) convex upwards large-scale cross-laminations. The strike of the stony horizons parallels the beach ridges seen at the top of the cliff. The axes of the scour and fill structures also tend to parallel the beach ridges, whereas the convex upwards cross-laminations tend to show migration towards land. Facies 3 is in direct connection with the beach ridges at the top of the cliff, and represents obvious beach sediments.

Trace fossils

Trace fossils of many kinds are present, but only three kinds will be considered here: burrows of the heart urchin *Echinocardium cordatum,* funnels made by the lugworm *Arenicola marina* and notches produced by *Pectinaria* sp. Besides these structures there are also trace fossils attributable to bivalve and crustacean activity. Specially conspicuous are escape traces of probable bivalves. Most of the traces are visible because of variations in concentration of the rather high proportion of heavy minerals in the sand. But the slightest difference in grain size also makes the trace stand out in the section in windy and dry weather, whereas the structures are almost invisible on rainy days and for many days afterwards. Because of these circimstances the section only rarely is in a satisfactory condition for study.

Lugworm funnels. Figs 9, 10, 11 & 17. Funnels made by *Arenicola marina* are often found in

Fig. 12. The J-shaped domichnion of Arenicola marina.

facies 1. Because these structures have their greatest extension in the vertical plane their appearance is highly dependent on the arbitrary section represented by the cliff (fig. 11). The funnels have a core of more or less structureless sand with or without vertical striations. The core is surrounded by only slightly disturbed sediment, the laminae of the contact zone being gently bent downwards. The depth of the funnels varies considerably, ranging from 5 to 30 cm. This type of funnel is restricted to sediment completely free of mud, as in the cliff. On the pseudo-tidal flat south of Læsø, where the sediment locally is muddy, the structures made by the lugworms are only funnel-shaped in the uppermost part, whereas they form narrow tubes in the lower part . Similar variations were described by Schäfer (1962: 341 & 410). In very rare cases the characteristic J-shaped domichnion of the lugworm is found (fig. 12). This takes the form of a narrow, light fill (the same colour as the sand that the worm feeds upon) coated with a dark layer of heavy minerals.

In general the funnels are largest near horizons of facies 2 and smallest in the middle of horizons of facies 1. Since facies 1 is supposed to have been formed at shallower water depths than facies 2, one should expect the middle part of facies 1 to represent the shallowest condition during a regression. It is wellknown that small lugworms prefer shallow water, and that the worms migrate to deeper water during their growth. Thus the distribution of different sized lugworm traces supports the transgression/regression model presented in the following.

In recent seas *Arenicola marina* lives at water

Fig. 13. Cross-sections of Echinocardium *burrows with visible backfilling structures.*

Fig. 14. The lower Echinocardium*-burrowed horizon in the eastern part of the cliff at Bansten Bakke, where the horizon may be more than 1 m thick and very intensively bioturbated.*

depths close to sea level, or more abundant within the intertidal zone. It should be emphasized that *Arenicola marina* has not been reported from bottom communities containing *Echinocardium cordatum*.

Heart urchin burrows. Figs 7, 9, 10, 12, 13, 14, 15 & 17. In association with facies 2 there are usually great numbers of burrows of heart urchins. Typically they are visible in cross-section and rarely identified in longitudinal sections, owing to poor development of the back-filling structure. In cross-section they are seen as circular to semicircular concentrations of heavy minerals corresponding to the outer limit of the locomotion trace. The semicircular cross-section

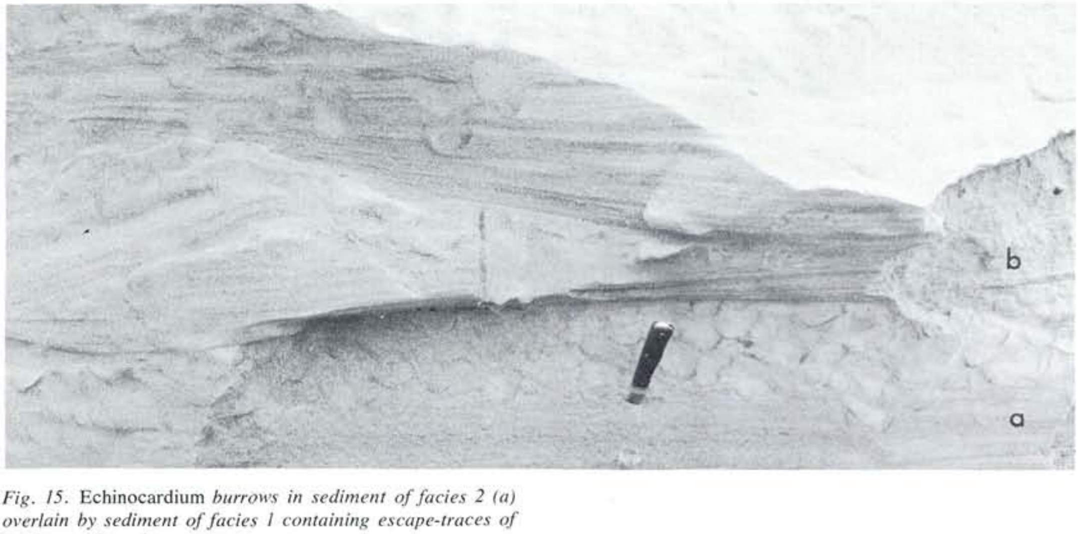


Fig. 15. Echinocardium *burrows in sediment of facies 2 (a) overlain by sediment of facies 1 containing escape-traces of* Echinocardium *(b).*

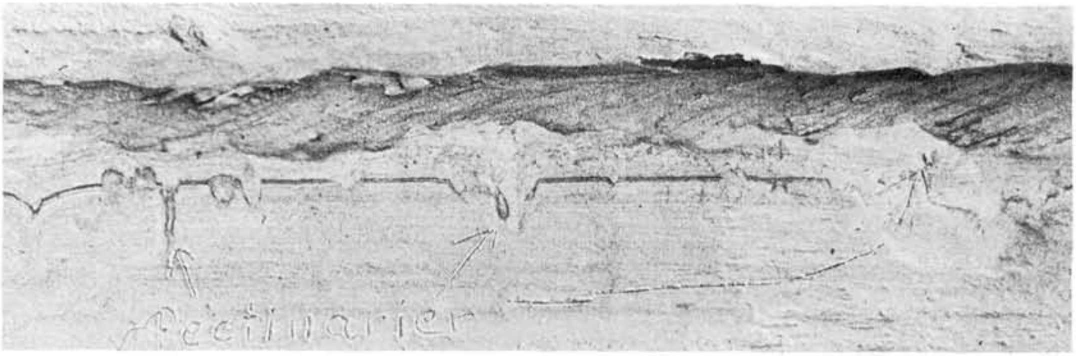


Fig. 16. Notches produced by Pectinaria *sp. in sediment of facies 2 overlain by an irregular erosion surface and sediment of facies 1.*

of most burrows – with the open end upwards – is either due to partial collapse of the roof or more commonly to truncation by a younger locomotion trace. The burrowing depth was c. 10 cm (fig. 9). Usually the animals burrowed in the horizontal plane in a meandering manner, but steeply inclined burrows have also been observed. Escape traces through more than 50 cm thick megaripples have been observed in some cases (fig. 15). These are straight and inclined at an angle of about 45°.

The structures here described resemble strongly those observed in living *Echinocardium cordatum,* by which species they are believed to have been formed: the burrowing depth rules out the possibility of any other heart urchin – see discussion and more complete bibliography in Bromley & Asgaard (1975).

At Bansten Bakke the heart urchins lived at water depths not exceeding 14 m. Concerning the entire triangular area they probably lived at water depths not less than 5 m and not exceeding 16 m (see discussion below). In the recent Kattegat sea Petersen (1893) found living *Echincardium cordatum* at numerous localities outside the 6 m contour, which seems strongly to control the distribution of the animals at localities free of mud, whereas at such localities they seem to have no lower limit at the water depths reaced in the recent Kattegat sea. In the Tyrrhenian Sea Hertweck (1971 & 1973) found that *Echinocardium cordatum* burrows are the most characteristic species of the ichnofacies below the wave-base.

Notches produced by Pectinaria *sp.* Fig. 16. The only body fossils found in the cliff are the agglutinating tubes of the polychaete worm *Pectinaria*. They are mainly found in the living position with the wide end of tube pointing downwards. Above the wide end of the tube a notch in the sediment lamination is commonly observed. These structures are particularly visible when found in connection with thin layers of heavy minerals. In most cases the notches are V-shaped in cross-section, but in many cases a small grabenlike structure is found instead (fig. 16). The borders of the notch then are defined by two or more minute normal faults. Notches after *Pectinaria* are found in both facies 1 and 2, but they are apparently most abundant in facies 1, where also reworked tubes are found.

Composite structures

Partial erosion of algal mats. Figs 5, 9, 11, 16, 17, 18 & 19. The cliff at Bansten Bakke exhibits several surfaces of irregular erosion. In all cases the eroded sediment is horizontally laminated, whereas the superposed layer always exhibits large-scale cross-lamination. The superposed ripples are mostly 10 cm high, but often larger. The ripple foresets are mainly straight, but curved convex upwards or concave upwards foresets also occur. The ridges and furrows of the erosion surfaces are in general weakly parallel (fig. 19). All those observed are more or less perpendicular to the ripple drift direction, but this might be due to the fact that they would be hardly visible if they were parallel to the ripple drift direction. In many cases the ridges have

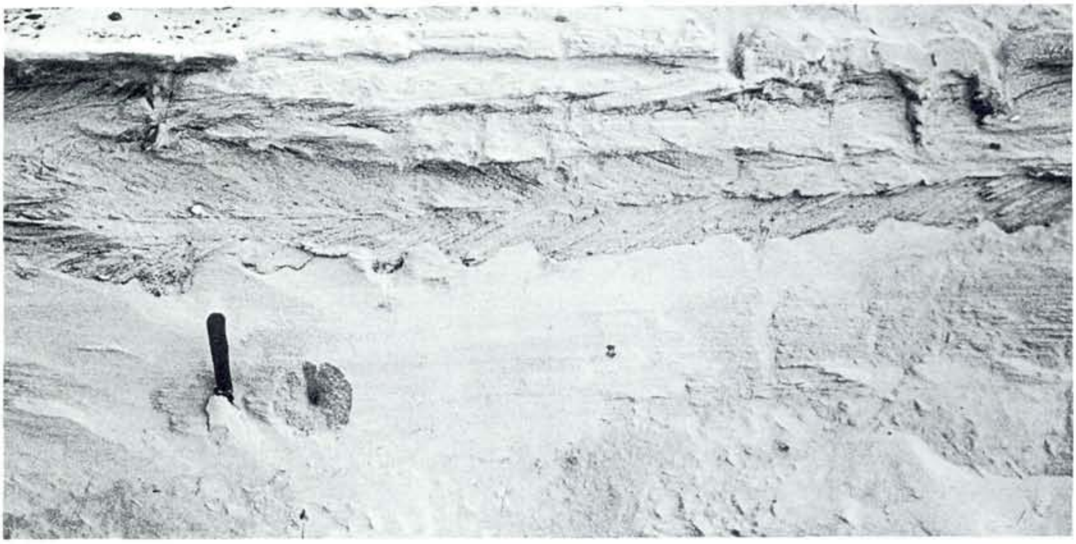


Fig. 17. Sediments of facies 2 and facies 1 separated by typical irregular erosion surface. The facies 2 sediment is intensively bioturbated by Echinocardium *as far as c. 20 cm below the erosion surface. A few* Arenicola *funnels are seen in various sections in the sediment above.*

small overhangs indicating that some binding agent must have been present. This agent is believed to have been sediment-binding algae, since the sediment is absolutely free of mud.

Recent structures similar to the irregular erosion surfaces exposed in the cliff are found at the pseudo-tidal flat south of Læsø (see above). There the structures obviously have been formed by partial erosion of the algal mat, since the ridges of these structures are capped by a greenish layer, 1–2 cm thick, in which numerous algal filaments can be seen when a piece of the sand is carefully broken. Newly formed furrows between the ridges are not capped by such a layer. However, the furrows are rapidly reinhabited by the algae, so the structures can be preserved during the next incursion of the sea.

It is obvious that these structures on the

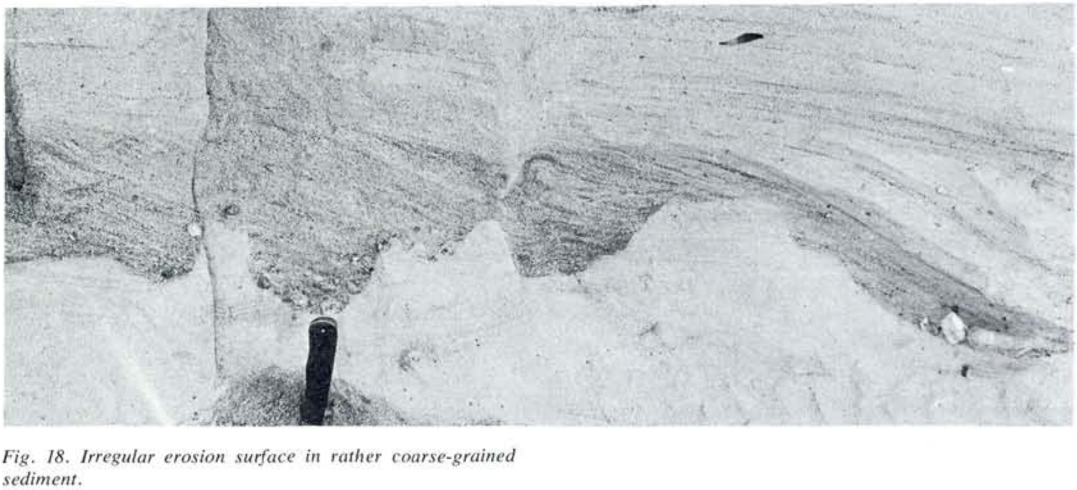


Fig. 18. Irregular erosion surface in rather coarse-grained sediment.

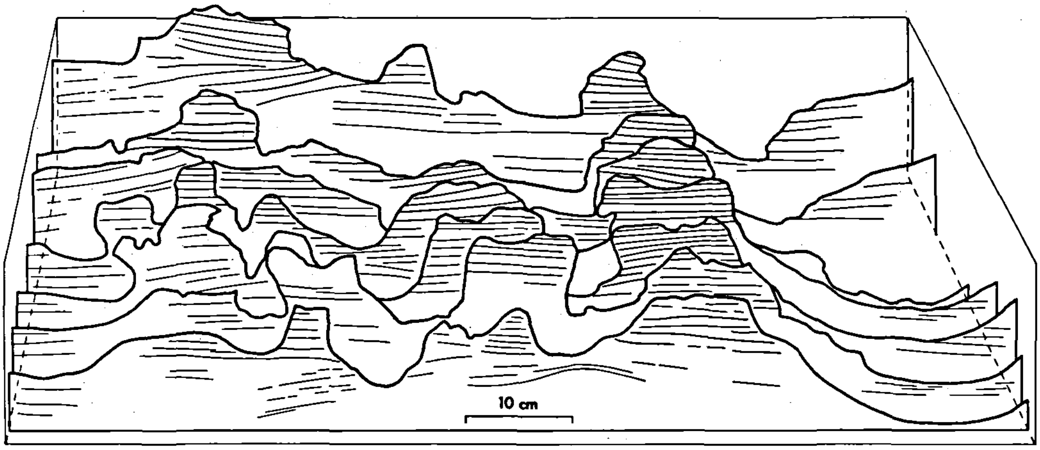


Fig. 19. Diagram showing a series of sections through an irregular erosion surface at Bansten Bakke.

pseudo-tidal flat are formed during very shallow conditions, either as a result of paddle-feeding by seagulls, or purely physically by the interaction between the sand-surface and the water-surface. Erosion occurs commonly at the pseudo-tidal flat, e.g. when the water leaves the flat and numerous small, very shallow ponds are formed. Along the borders of these ponds small waves constantly erode the looser parts of the algal mat, thus forming ridges and furrows more or less perpendicular to the borders of the ponds.

If not formed by partial erosion of algal mats under very shallow conditions, similar to what is found at the pseudo-tidal flat, the irregular erosion surfaces found in the cliff might have been formed by partial erosion of algal mats under stronger current conditions than are known from the present Kattagat sea. Spärck (1926) and Steemann-Nielsen (1939) found faunal indications on the presence of tidal currents during early postglacial time. This hypothesis is supported by the fact that the fossil irregular erosion surfaces generally are better developed than those occurring at the pseudo-tidal flat, and also by the fact that the cross-bedding structures of facies 1 at Bansten Bakke are larger than similar structures at thepseudo-tidal flat, where horizontal lamination and small-scale ripples are the most common structures. Furthermore, the herringbone structures commonly found in the cliff at Bansten Bakke may also indicate stronger tidal current conditions in early postglacial time.

Gas-expulsion structures. Figs 20 & 21. Gas-expulsion structures are commonly found in the western part of the cliff. Structures of this type are in general irregular V or U-shaped, 0.5 to 1 m high and with a piece of algal peat at the bottom. Internally the structures are vertically striated by concentrations of heavy minerals, completely obscuring primary sedimentary structures, while the surrounding sediment is not disturbed.

It is suggested that structures like this are formed by upwards migration of numerous small gas-bubbles developed by decomposition of algae, which in this way are converted to the algal peat found at the bottom of the structures.

Such structures might have been caused by rhythmic changes in the hydrostatic pressure, e.g. under tidal conditions. But the effect of transgressions and regressions should also be considered, since the bottom of the structures mostly are found in facies 2 (transgression) and the top in facies 1 (regression). Förstner & al. (1968) described similar expansion of gas-bubbles in sediment caused by changes in the hydrostatic pressure.

Geological interpretation of the sedimentary structures

Keeping in mind that the cliff represents a cross-section through an old tongue of land, it is clear that the sediment exposed in the lower part

Fig. 20. Gas-expulsion structure. Basis of structure in sediment of facies 2, top in facies 1.

of the cliff represents a cross-section through a submerged shoal. During the postglacial transgressions and regressions such a shoal must have been sensitive to changes in sea level.

The cliff section is composed of three minute fining upwards sequences each followed by a coarsening upwards sequence both in respect to structures and to grain-size. Furthermore, these sequences correspond to particular sedimentary structures so that the transition from fining upwards sequences in each case is linked to facies 2 and the burrows of *Echincardium cordatum*, whereas the transition from coarsening upwards sequences to fining upwards sequences in each case is linked to facies 1 and funnels made by *Arenicola marina*.

It is generally accepted that fining upwards sequences in marine sediments may be formed during transgressions, and coarsening upwards sequences during regressions. Both facies involved belong to the lower flow regime, but facies 1 obviously belongs to a higher energy level than facies 2. This is probably to be correlated to changes in water depth, with the lowest energy level in the deepest water.

Thus the physical sedimentary structures *alone* allow the postulation of three postgacial transgressions intercallated with regressions before Læsø became a stable island. Since the cliff shows no major erosional surfaces (except that immediately above the Yoldia clay, which probably coincides with the Ancylus time) we may also postulate that the transgressions reflected in the cliff section may be the oldest known from the postglacial history of Denmark. Three Atlantic and one Subboreal transgression are known from Denmark (Iversen 1937, Troels-Smith 1942, Krogh 1965). As discussed elsewhere the extensive beach ridges and dead cliffs surrounding the old triangular part of Læsø are related to a late Subboreal transgression and probably may also be related to an earlier Subboreal transgression. Thus the similarity between what is found at Læsø and what is known from other parts of Denmark seems striking. On the other hand Mörner (1969) found a long series of postglacial transgressions at the Swedish west coast. If his hypothesis is correct several transgressions must be included in the same *Echincardium* burrowed layer. This could be so, especially in the case of the lowermost layer, which probably was formed during the deepest water conditions where the magnitude of the regressions would hardly affect the sedimentary structures. According to Mörner the postglacial limit at Læsø should be found 8 m above present sea

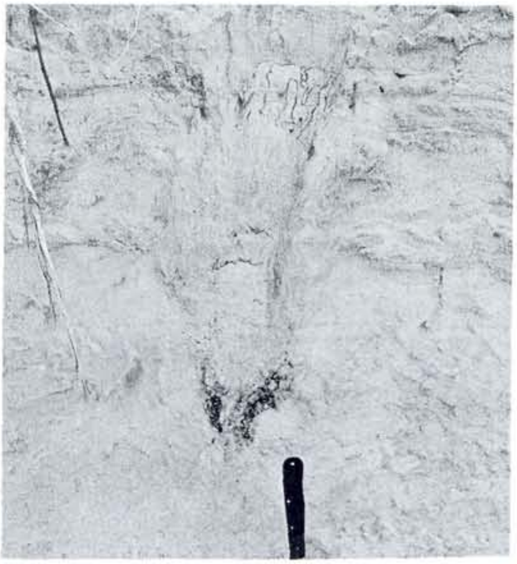


Fig. 21. Gas-expulsion structure. At the base of the structure the algal peat is clearly visible.

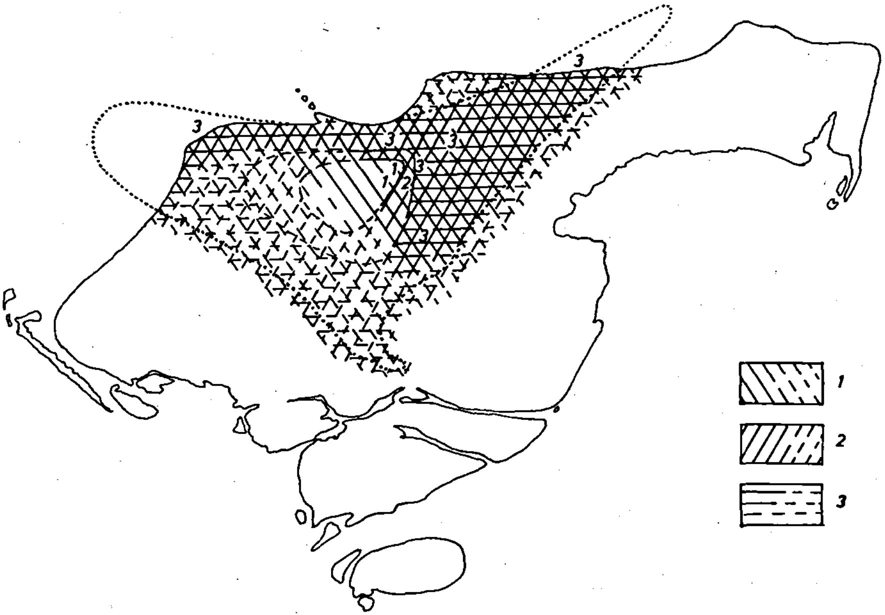


Fig. 22. The distribution of sediments of facies 2. 1: Only one horizon (the lower) present. 2: two horizons (the lower and middle) present. 3: three horizons present. The distribution of the middle and upper horizon may roughly correspond to the shape of the initial growth stages of Læsø.

level. However, at Læsø beach sediments are found up to 11 m above sea level, and since these sediments do not even represent the postglacial limit (Jessen 1897), it seems unlikely that Læsø followed the same pattern of isostasy as the Swedish west coast.

The cliff taken as an entity forms one major coarsening upwards sequence. This corresponds to a regressive tendency in spite of the transgressions. Facies 1 horizons contain irregular erosion surfaces that are believed to have been formed by partial erosion of algal mats under shallow conditions. In the uppermost horizon of facies 1 there is also a deflation surface. But in the lowest part of the cliff no such structures are found that could be interpreted as the result of exposure to the air. The interpretation of the cliff on the basis of physical sedimentary structures alone is therefore that a long-ranging postglacial regression interrupted by at least three transgressions has taken place and thus formed the 'pre-emergence' part of Læsø.

The lateral extension of facies 2 has been investigated by examination of the original descriptions of ten boreholes penetrating the oldest part of Læsø at Højsande. Some of these boreholes have been published by Michelsen (1967). In boreholes 4, 8 and 9 no differentiation can be made between facies 1 an 2 because of very homogehous grain-sizes. In seven boreholes however, one to three fining upwards sequences with intercallated coarsening upwards sequences can be distinguished, thus indicating the presence of one to three horizons of facies 2 in the boreholes. This is supported by finds of shell-fragments and spines of *Echinocardium cordatum* in fine-grained sediment in some of the boreholes.

Fig. 22 shows the supposed extension of horizons with facies 2. The lowermost horizon extends over the whole area, whereas the middle does not occur in boreholes 2 and 6, and the uppermost horizon does not occur in boreholes 2, 3 and 6. Thus the extension of the middle and uppermost horizons roughly corresponds to the shape of the initial growthlines of Læsø.

From the cliff north of Vesterø Havn (Jessen 1897, Michelsen 1967) Mörner (1969) described three fine-grained horizons separated by more coarse-grained shore sediments. Because of poor exposure during the last ten years the cliff has not been studied in detail. However, both

Echinocardium burrows and *Arenicola* funnels have been observed in the cliff, indicating a development of this part of Læsø similar to that found at Bansten Bakke.

Furthermore, in a pit at the southwestern margin of the old triangle near Vesterø Mejeriby *Echinocardium* – burrowed layers are found below shore sediments 4.5 m above sea level (theodolite measurement).

Comparing the cliffs at Bansten Bakke and Vesterø Havn, the ten boreholes and the pit near Vesterø Mejeriby it seems evident that the alternation between sediments formed at shallow water and deeper water respectively is not a local phenomenon occurring only at Bansten Bakke, but rather a feature reflecting events of regional significance.

No horizons in the ten boreholes are characterized by stony horizons similar to those known from beach ridges. It therefore seems unlikely that Læsø emerged as a stable island before the completion of the three transgressions, but rather that the entire area represented a shoal occasionally exposed to the air during the last regression maximum. Mörner (1969 p. 388) mentions the occurrence of eolian sand with structures derived from frost activity in the lowermost fine-grained horizon in the cliff at Vesterø Havn. The present author has not been able to confirm this observation, but is of the opinion that the structures mentioned are bivalve escape traces, which may be confused with ice-wedge structures.

According to Mertz (1924) the Littorina transgressions in Vendsyssel (north Jylland) reached c. 14 m above present sea level at localities along the isobase transecting the cliff at Bansten Bakke. At Læsø the trangressions may be considered to have reached approximately the same level. Facies 2 horizons are found from 2 m below to 9 m above present sea level. Sediment of this type therefore must have been formed at water depths between 5 and 16 m. Further calculations of water depths greatly depend on when precisely the Littorina transgressions reached their maximum in this area. It is believed that this happened during the first of these transgressions since the lowermost horizon of facies 2 seems to cover the entire island, whereas the two upper horizons are limited to lower areas.

In southern parts of Denmark the Littorina transgressions reached their maximum extension during Subboreal time (Troels-Smith 1940, 1942; Krog 1968) or even later (Mikkelsen 1949), whereas the transgression maximum was reached in mid-Atlantic time in Dybvad in Vendsyssel (Iversen 1943). Thus this investigation supports the idea that the maximum of the Littorina transgression took place earlier and earlier the farther northwards one goes, which is simply explained by the difference in magnitude of the isostatic recovery during postglacial time.

In the cliff section at Bansten Bakke the lowest *Echinocardium*-burrowed layer (facies 2) is found between 0 and 1 m above present sea level, while the uppermost layer is found up to 3.5 m above the sea. Therefore it seems reasonable to suggest that *Echinocardium cordatum* in the cliff area lived at water depths of c. 14 m during the first transgression, and at water depths between 10.5 and 5 m during the last transgression maximum.

The interpretation of the physical sedimentary structures is strongly supported by trace fossils and composite structures. However, there seems to be a discrepancy between several earlier authors and the present author concerning the magnitude of the regressions between the transgressions reflected in the cliff. Since *Echinocardium cordatum* in the recent Kattegat sea lives at water depths greater than 6 m, and since *Arenicola marina* is most abundant in the inter-tidal or pseudo-tidal zone (and a little lower) it requires shorelevel displacements of the magnitude of 5 m between each transgression and regression to explain the alternation of *Echincardium*-burrowed and *Arenicola*-burrowed layers in the upper part of the section. Mörner (1969) operated with regressions of the magnitude of not more than 1 m. However, it should be emphasized that studies on beach ridges do not give any direct information about the magnitude of the regressions, since sediments formed during the maximum extension of the regressions are covered by beach ridges or marine sediments deposited during later transgressions. The alternation of *Echinocardium*- and *Arenicola*-burrowed layers may therefore be explained by a much broader inter-tidal zone than known from the recent Kattegat sea. This is supported by the existence of 'herringbone' structures, gas-expulsion structures, a deflation surface, irregular erosion surfaces, and by the faunal investigations by Spärck (1926) and Steemann-Nielsen (1939).

Age of the old part of Læsø

In 1872 a skeleton of a sperm whale (*Physeter catodon*) was found NE of Byrum at an altitude of c. 4.5 m close to the foot of the beach ridge surrounding the old triangular part of Læsø. A tooth of this whale has been C^{14}-dated by H. Tauber. The age of the tooth is 980 ± 80 years BC. The find was described with exceptional care by the local doctor (Jensen 1872). His description makes it possible to state that the whale was contemporaneous with the beach ridges surrounding the old triangular part of Læsø, or slightly younger. Unfortunately it has not been possible to find other fossils which can be used for C^{14} dating.

The beach ridge is complex where the whale was found. This can also be seen in the cliff section at Bansten Bakke, and in the area between Byrum and Vesterø Havn, where the beach ridge splits in two. To the north there is a strong beach ridge running along a straight line from Byrum to Vesterø Havn, and to the south there is a dead cliff at Byrum passing into a beach ridge south of Vesterø. The age of the whale is thus contemporaneous with the dead cliff, or slightly younger, i.e. late Subboreal. The older part of the beach ridge complex then may be related to an earlier Subboral transgression.

By aid of his shorelevel displacement curve Mörner (1969) related this beach ridge complex to postglacial transgression maxima 5B and 6, which he dated to 3.650 BC and 2.100 BC respectively. The age of the whale (980 BC) as well as the presence of beach ridges 11 m above sea level at Læsø, where the postglacial limit according to Mörner should be expected 8 m above sea level, demonstrates that the shorelevel displacement curve calculated by Mörner at the Swedish west coast does not fit to structures and ages found at Læsø.

Conclusions

The sedimentary history of Læsø falls into two distinct stages. During earlier stages Læsø formed a shoal inhabited by the heart urchin *Echinocardium cordatum* during periods of transgression and by the lugworm *Arenicola marina* during periods of regression. During later stages Læsø became a stable island and numerous beach ridges were formed. The oldest beach ridges are found at altitudes of only 11 m above present sea level. This indicates that Læsø remained a shoal until after the maximum Littorina transgression, which in southeastern Vendsyssel took place during mid-Atlantic time. However, since it is a general tendency that the maximum transgression began earlier the farther northwards one goes perpendicular to the isobases, it is to be expected that the maximum transgression at Læsø took place still earlier.

The cliff at Bansten Bakke shows a general lowering of the sea level during early stages of Læsø's history. The lower *Echinocardium*-burrowed horizon is by far the thickest, and above this horizon neither funnels made by *Arenicola marina* nor irregular erosion surfaces have been found as is the case in the upper part of the section. These features seem to indicate that the maximum transgression coincides with the first transgression, which in other parts of Denmark took place during early Atlantic time. Moreover, the alternation of *Echinocardium*- and *Arenicola*-burrowed horizons, the latter containing 'herringbone' structures, gas-expulsion structures, a deflation surface and irregular erosion surfaces, seems to indicate the presence of stronger tidal currents than are known in the recent Kattegat sea.

The shoal sediments in the cliff are capped by beach ridges, which can be traced to the place where the skeleton of a sperm whale was found. C^{14} dating of a tooth of the whale gave an age of 980 ± 80 years BC, i.e. late Subboreal. In the cliff it is obvious that this beach ridge is complex since it is built up in places by two thick stony horizons separated by sand containing bivalve trace fossils. The stony horizons are found from 2 to 7 m above present sea level. The younger part of these stony horizons thus seems to be contemporaneous with the whale, while the older part seems to be contemporaneous with the straight beach ridge north of the dead cliff between Byrum and Vesterø.

Certainly, it is tempting to correlate this older part of the beach ridge with the early Subboreal transgression, and the three *Echinocardium*-burrowed horizons with the three Atlantic transgressions (Iversen 1937 & 1943). However, according to Mörner (1969) that model seems to be inaccurate since he found a large number of postglacial transgressions at the Swedish west coast. Although his shorelevel displacement curves fit very badly at Læsø, it is nevertheless believed that more than four postglacial transgressions have taken place. Before Læsø became a stable island at least three transgressions took place. This is seen in the cliff at Bansten Bakke. Before the completion of the old triangle at least one further transgression took place. This is reflected by a c. 2 km long and 1 m high dead cliff starting from a point c. 2 km east of Vesterø Havn. And finally, before the death of the whale two transgressions took place to form the dead cliffs and beach ridges surrounding the triangle. This means that at least 6 transgressions have taken place between the formation of the Yoldia Clay (10.960 ± 180 BC) and the formation of the dead cliffs and beach ridges surrounding the old triangular part of Læsø (980 ± 80 BC).

Acknowledgements. Thanks are given to Richard G. Bromley, Ulla Asgaard, Claus Heinberg, Niels Just Pedersen and Lars Clemmensen for many useful discussions. Richard G. Bromley improved the English of the manuscript. Jan Ågaard and Henrik Egelund improved the figures.

Dansk sammendrag

Læsøs sedimentære historie belyses ved tolkninger af øens strandvoldssystemer og af de ofte meget velbevarede sedimentstrukturer, som kan ses i klinterne langs nordkysten. Gravegange efter sømus og sandorm karakteriserer lag afsat på henholdsvis dybt og lavt vand. De sømus-gravede lag findes i tre horisonter, som anses for at repræsentere havstigninger, der fandt sted endnu inden Læsø existerede som ø. Mellem de sømus-gravede lag findes sandorm-gravede lag, som anses for at være dannet i perioder med havsænkninger. Dette bekræftes af rent fysiske sedimentstrukturer, idet de sømus-gravede lag domineres af sedimentstrukturer, der ofte dannes på forholdsvis dybt vand, mens de sandormgravede lag domineres af sedimentstrukturer, der oftest dannes på lavere vand. Bl. a. forekommer der hyppigt uregelmæssige erosionsflader i de sandorm-gravede lag. Desuden forekommer der en enkelt afblæsningsflade. De uregelmæssige erosionsflader tolkes som opstået ved delvis erosion af algemåtter under medvirken af betydeligt stærkere tidevandsstrømninger end kendt fra det nuværende Kattegat.

En markant diskordans findes mellem strandvoldene på den lavtliggende del af Læsø og de strandvolde, som dækker den ældre, højtliggende del, idet den ældre del omgives af indlandsklinter og særligt veludviklede strandvolde. Indlandsklinterne anses for at være dannet ved erosion under en yngre Subboreal havstigning. Efter Subboreal tid er Yoldialeret, hvorpå Læsø er aflejret, hævet så meget, at dets overflade over store strækninger er næsten sammenfaldende med havoverfladen. Herved blev de vidtstrakte meget lavvandede sandflader (pseudotidale flader) dannet syd for Læsø. Særegne sedimentstrukturer karakteriserer disse sandflader, specielt uregelmæssige erosionsflader opstået ved delvis erosion af algemåtter. Disse strukturer ligner i høj grad strukturerne i de ældre dele af Læsøs sedimenter.

På basis af sedimentstrukturerne, som kan ses i klinterne langs nordkysten, kan det konkluderes, at Læsø under de første tre eller flere havstigninger var fuldstændig vanddækket, og at de største vanddybder opnåedes under den første havstigning. Endelig kan det på basis af bl.a. en kulstof-14 datering af en kaskelothval og på forekomsten af indlandsklinter på den ældre, højtliggende del af Læsø konkluderes, at der i tidsrummet mellem dannelsen af Yoldialeret og kasketlothvalens død har fundet mindst 6 havstigninger sted.

References

Bromley, R. G. & Asgaard, U. 1975: Sediment structures produced by a spatangoid echinoid: a problem of preservation. *Bull. geol. Soc. Denmark* 24: 261–281.

Förstner, U., Müller, G. & Reineck, H.-E. 1968: Sedimente und Sedimentgefüge des Rheinlandes im Bodensee. *Neues Jahrb. Mineral. Abhandl.* 109: 33–62.

Hertweck, G. 1970: Fährten und Spuren im Watt. *In:* Reineck, H.-E., Dörjes, J., Gadow, S., Hertweck, G. & Wunderlich, F.: *Das Watt. Ablangerungs- und Lebensraum.* 108–123. Frankfurt am Main: Kramer.

Hertweck, G. 1971: Der Golf von Gaeta (Tyrrhenisches Meer). V. Abfolge der Biofaziesbereiche in den Vorstrand und Schelfsedimenten. *Senckenbergiana marit.* 3: 247–267.

Hertweck, G. 1973: Der Golf von Gaeta (Tyrrhenisches Meer). VI. Lebenspuren einiger Bodenbewohner und Ichnofaziesbereiche. *Senckenbergiana marit.* 5: 179–197.

Iversen, J. 1937: Undersøgelser over Litorinatransgressioner i Danmark. *Meddr dansk geol. Foren.* 9: 223–232.

Iversen, J. 1943: Et Litorinaprofil ved Dybvad i Vendsyssel. *Meddr dansk geol. Foren.* 10: 324–328.

Iversen, J. 1967: Naturens udvikling siden sidste istid. *In:* Danmarks Natur vol. 1. København: Politiken. 100 pp.

Jensen, 1872: *Unpublished letter to Prof. Japetus Steenstrup concerning the find of a fossil whale, 10th November 1872.* Det kongelige Bibliotek. København.

Jessen, A. 1897: Beskrivelse til geologisk Kort over Danmark. Kortbladene Læsø og Anholt. *Danmarks geol. Unders.* (2) 4: 48 pp.

Jessen, A. 1920: Stenalderhavets Udbredelse i det nordlige Jylland. *Danmarks geol. Unders.* (2) 35: 112 pp.

Jessen, A. 1936: Vendsyssels Geologi. *Danmarks geol. Unders.* (5) 2: 195 pp.

Krog, H. 1965: On the Post-glacial development of the Great Belt. *Baltica* 2: 47–60.

Krog, H. 1968: Late-Glacial and Postglacial Shoreline Displacements in Denmark. *In:* Morrison, R. B. & Wright Jr., H. E. (eds.): *Means of correlation of Quaternary successions 8: 421–435.*

Mertz, E. L. 1924: Oversigt over de sen- og postglaciale Niveauforandringer i Danmark. *Danmarks geol. Unders.* (2) 41: 50 pp.

Michelsen, O. 1967: Foraminifera of the late-quaternary deposits of Læsø. *Meddr dansk geol. Foren.* 17: 205–264.

Michelsen, O. 1968: Geologi. *In:* Johansen, H. & Remmer, L. (eds.): *Kattegatøen Læsø. Naturen og mennesket.* Byrum: Remmer. 10 pp.

Mikkelsen, V. M. 1949: Præstø Fjord. The development of the post-glacial vegetation and a contribution to the history of the Baltic Sea. *Res. Botanicae Danicae* 13: 171 pp.

Mörner, N.-A. 1969: The Late Quaternary history of the Kattegat Sea and the Swedish west coast. *Sveriges geol. Unders.* (C) 640: 487 pp.

Petersen, C. G. J. 1893: *Det videnskbelige Udbytte af Kanonbåden "Hauchs" Togter i de danske Have indenfor Skagen.* Atlas I–III. København.

Schäfer, W. 1962: *Aktuo-Paläontologie nach Studien in der Nordsee.* Frankfurt am Main: Kramer. 666 pp.

Schou, A. 1945: *Det marine Forland.* København: Hagerup. 236 pp.

Spärck, R. 1926: *On the food problem in relation to marine zoography.* Physiological Papers dedic. to prof. August Krogh. København.

Steemann-Nielsen, E. 1939: De danske Farvandes Hydrografi i Litorinatiden. *Meddr dansk geol. Foren.* 9: 337–350.

Tauber, H. 1966: Danske kulstof-14 dateringsresultater II. *Meddr dansk geol. Foren.* 16: 153–176.

Troels-Smith, J. 1940: Stenalderbopladser og Strandlinier på Amager. *Meddr dansk geol. Foren.* 9: 489–508.

Troels-Smith, J. 1942: Geologisk Datering af Dyrholm-Fundet. *Kgl. Danske Vidensk. Selsk. Arkäol.-Kunsthist. Skr.* 1: 137–212.

Developmental history of the River Gudenå, Denmark

KAJ HANSEN

Hansen, K.: Develomental history of the River Gudenå, Denmark. *Bull. geol. Soc. Denmark*, vol. 26, pp. 237–250. Copenhagen, December 2nd 1977.

New observations on the terrace levels in the east Jylland valley systems indicate that Ussing's (1904, 1907) view of the Falborg Stage is correct. On the other hand, his explanation of the Skalså Stage, and the retreat of the ice from Falborg Stage to Skalså Stage, requires further examination, since the explanations so far offered do not hold. Further study is needed on the development of the lake systems of the Gudenå and connecting valleys since a number of different processes appear to be responsible for these erosion forms. The present study appears to show that the last glacial advance (Baltic Phase) has not influenced the morphology of the area to any great degree. The topographic expression of the land definitely owes its origin to older glaciations, to the processes that follow with both glacial advance and retreat.

Kaj Hansen, Gammeltoftsgade 16, 1355 København K, Denmark. August 16th, 1977.

In 1896 Gerard de Geer published his book "Om Skandinaviens geografiska Utvickling efter Istiden" (On the geographical development of Scandinavia after the Ice Age), which caused strong protests both in Sweden and in Denmark, in Sweden because de Geer maintained that there had been two glacial eras in Scandinavia, in Denmark because he placed the outer limits of the last glaciation across Jutland along the bottom of the fjords from south to north ending in Mariager Fjord.

This was the reason why Ussing (1903) wrote his treatise on the outwash plains of Jutland, in which he proved that the outer limit of the last glaciation lay somewhat further to the west; and at Dollerup the limit had curved to the west continuing to the North Sea near Bovbjerg. In several treatises in the following years (1904 and 1907) Ussing offered further evidence in support of his ideas as to where the border of the ice had been and the progress of the melting; thus he divided the period of melting into three stages: The Falborg stage, the Skalså stage, and the Gudenå stage.

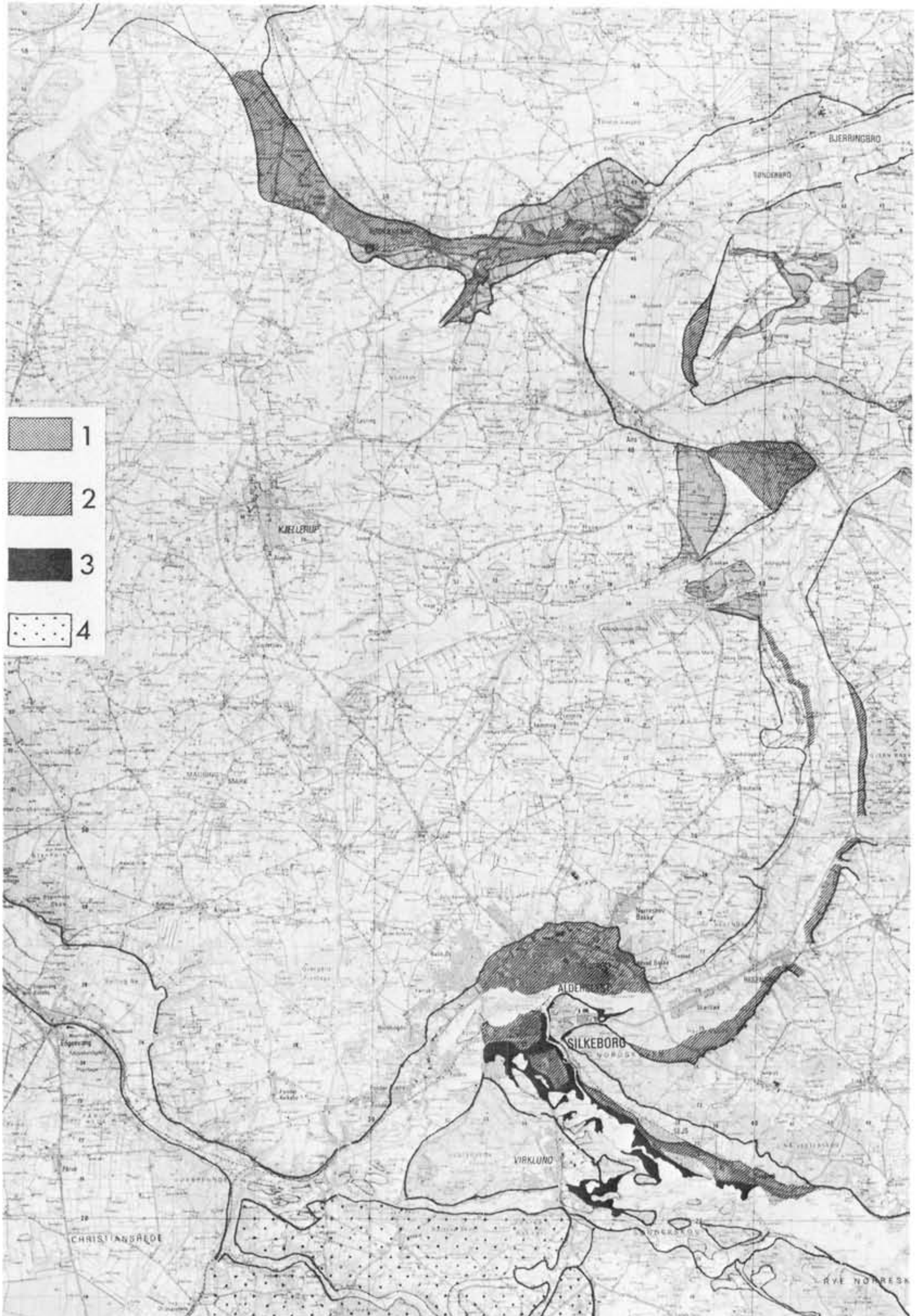
Ussing's treatises excited great interst and right up to the present they have been considered some of the safest tracts within Danish Quaternary geology. However, the more one concerns oneself with the details the more difficult it becomes to make Ussing's theories fit.

In the present paper the Gudenå valley between Silkeborg and Randers will be treated first, and after that the valley containing Julsø, Borresø, and Torsø together with the Silkeborg area (fig. 1).

The Falborg Stage

Ussing wrote (1907) that the upper end of the Falborg plain is only incompletely preserved. The direction of the plain here is west-east, only the northern part – without any slope of erosion – continues into a somewhat higher moraine landscape (at Vindum), where it is most likely that the border of the ice lay, at least during part of the formation of the Falborg plain. The southern part of the Falborg plain ends to the east in a slope down to the river Gudenå, where it was apparently eroded away by the glacial predecessor of the Gudenå.

In the Falborg valley there are terraces on two levels, 38 m and 30 m. At the northern side of the Falborg valley the 38 m level is seen in one piece from south of Vindum to Rødkjærsbro, but very much cut up by the erosion of the eastern parts. Furthest to the east the width of the terrace is 1600 m, but to the west it narrows down, and at Rødkjærsbro the terrace quite disappears. At the southern side the terrace is narrower and con-


1
2
3
4
BJERRINGBRO
SØNDERBRO
KJELLERUP
SILKEBORG
VIRKLUND
CHRISTIANSHEDE
RYE NØRRESK

tinues into Levring Bæk valley in order to disappear completely at the Østervandet.

Ussing (1907) wrote furthermore that it seems as if the Falborg valley originally continued to the south for a rather long distance, as at several places in the Gudenå valley he found terraces at levels just as high or higher than the 38 m stage in the Falborg valley.

To this phase of the Falborg stage the 1.5 km wide dry valley also belongs; from the Allingå valley at Grønbæk it stretches northwards to the Gudenå valley south-east of Ans. The northern part of the valley stands with a 27 m high slope towards the lake Tange Sø, and its bottom is 40–45 m above sea level.

Ussing regarded the valley as part of the Gudenå valley, but it was also an outlet for the lake Hinge Sø of that time and for the whole area between Gudenåen and Karup outwash plain.

NW and SE of Grønbæk there are terraces at the same level, and further southwards at the western side of the Gudenå opposite Tvilum Kirke there is a terrace 42 m above sea level. The 38 m stage can further be traced into some of the rivulets at the eastern side of the Gudenå (Hansen 1971).

The 30 m phase forms the bottom and the watershed in the Falborg valley. At the southern side of the valley it forms a terrace from Tange to Levring Bæk. From here and further on to the west the bottom of the valley itself lies at this level, which can also be traced through the Gudenå valley to the south.

Along the east side of Tange Sø, beneath an 11 m high straight slope there is a terrace (surface), the innermost edge of which is 30 m above sea level.

NE of the dry valley on the ridge that reaches into the meander bow of the Gudenå there is also a plain at 30–32 m above sea level, and from the point where Allingå flows into the Gudenå valley and southwards this level is found as wider or narrower terraces as far as the lake Silkeborg Langsø. Both the wide terrace north of Silkeborg

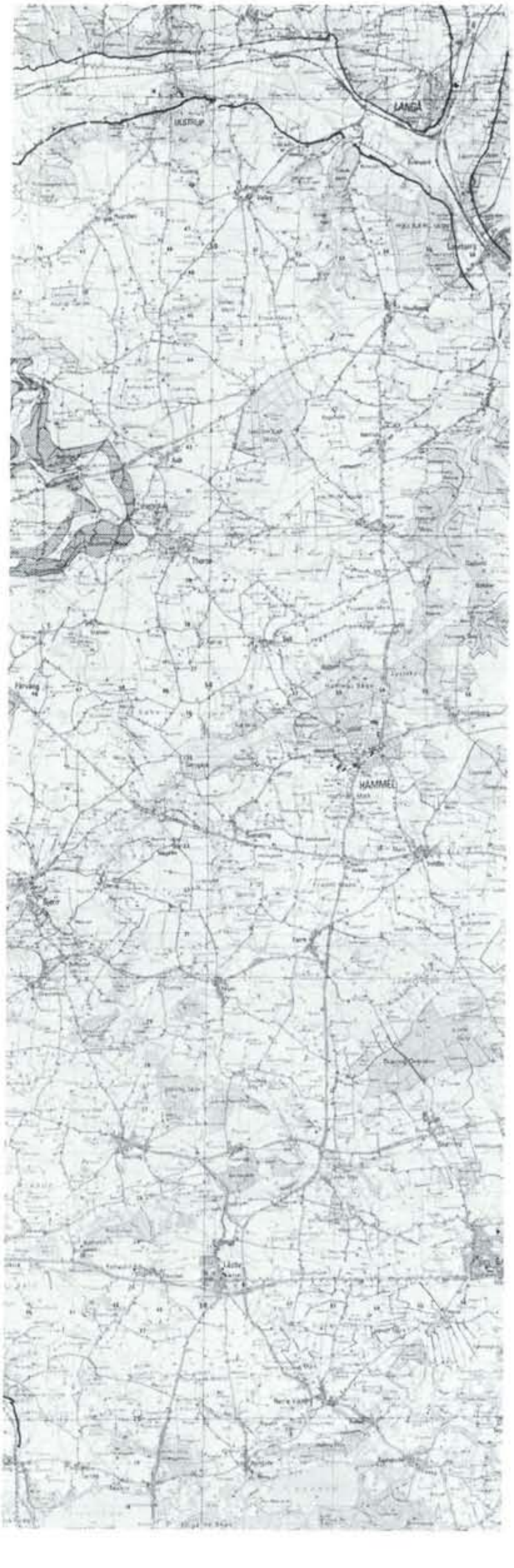


Fig. 1. Map of the area of study, reproduced by Copenhagen University, Geographical Institute, with permission (A454/72) of the Geodetic Institute. 1. Terrace surfaces belonging to Falborg valley's older stage. 2. Terraces belonging to Falborg valley's later stage. 3. The Gudenå's lower terrace. 4. Areas older than the last glaciation.

Fig. 2. The dry valley at Langå between the Nørreå valley and the Gudenå valley. The hills in the background are the northern side of the Nørreå valley.

Langsø and the riverplain on which Silkeborg lies are at the same level, which is also the uppermost level of the terrace lying along the northern side of Remstrup Å, Brassø, Borresø, to the western end of Julsø. This is in complete accordance with Ussing's opinion (1904) that at the beginning of Stage IV the melt water from the area south of Silkeborg was admitted to the Falborg valley.

The Skalså stage

As to the fifth stage of the melting of the ice, the Skalså stage, Ussing (1904) wrote only that the ice had now retreated so far that the river had disappeared from the Falborg valley, as the water could now follow the lower Gudenå valley almost as far as to Randers, but that it probably had to flow to the west, because the ice covered Kattegat. The river must have used part of the old fjord valley, where Nørresø now lies, and further on its way it must have used the Skalså valley.

Later on Ussing (1907) treated this stage in greater detail. At Onsild Bridge the bottom of the Skalså valley is 7 m above sea level, and the older terraces of the valley sides rise as far as 20 m above sea level. 10 km NW of Randers the Skalså valley bends abruptly to the west past the place where the present little Skalså emerges from the highland surrounding Lake Fussing. The course continues in zigzag fashion through a connecting valley, the Gudenå valley near Langå, having used over a certain distance the present Nørreå valley. This, Ussing thought, is made probable by the fact that in these parts of the Nørreå valley there are sizeable deposits of sand whose highest terraces reach 12-16 m above sea level, and by the presence of the southernmost connection canal, the valley from the Nørreå southwards to the Gudenå valley north of Langå, a part that is now dry (fig. 2). This part of the valley might have been formed precisely by a river like the one mentioned. Ussing stated that the sand bottom in the middle of this part of the valley has a height of 6-10 m above sea level, and that there are terraces at a height of 12-22 m above sea level along the sides of the valley.

Apparently this dry valley north of Langå inspired Ussing with the idea of a Skalså stage during the withdrawal of the last ice cover, but he completely overlooked the fact that between the present Nørreå valley and the original Nørreå valley there is a threshold 15 m above sea level, and that this would have caused the formation of an ice dammed lake when both Nørreå valley and Gudenå valley to the east were barred by ice. This lake would have included the whole Nørreå valley and its continuation to the west in Vedsø and the Viborg-Hald valley in addition to the Gudenå valley as far up as to Grønbæk. The water surface of such an ice dammed lake would have been at least 15 m above sea level. There is nowhere the slightest sign of such an event having taken place.

Hartz & Østrup (1899), in their treatment of the interglacial diatomaceous earth occurrence at Hollerup, wrote that the lake where these diatoms were deposited had reached so far as out into the present Gudenå valley, which at the time either did not exist or did not go so far north. They also stated that the diatomaceous earth is only covered by glaciofluvial sand from de Geer's second ice era. Now this was written before Ussing showed the limit of the last glaciation along Karup outwash plain, but it is right that there is only sand from the meltwater covering the diatomaceous earth.

Milthers (1913) believed he could demonstrate the following series of strata in these areas:
Uppermost stoneless clay marl
Upper till
Interglacial diatomaceous earth
Stoneless clay marl
Lower till.

He also maintained that both Nørreå valley and the lower Gudenå valley are tunnel valleys which existed in the latest interglacial time. Now both his maps and the text show that he has nowhere any complete section through the whole series of strata. His upper till is only known from two localities, both lying west of Gudenå at Tange. His stoneless clay marl is almost limited to an area far to the north and west of the Gudenå, and his whole series of strata is highly dubious, for everywhere in the borings Tertiary clay and sand are overlain by glaciofluvial deposits. This is characteristic of large parts of mid-Jylland as far down as the Salten valley.

The dry valley north of Langå between the Gudenå valley and Nørreå valley (fig. 1) is 800 m wide in the northern part, and it has the same width southwards almost as far as to Helstrup. Here the valley widens like a funnel, and at the outfall into Gudenå valley it is 1200 m wide. At the nothern end the bottom is 9.5 m above sea level, and southwards it slopes down to 8 m where it opens into the Gudenå valley. The strange thing is that both to the north and to the south it stands with a steep slope 6 m above both Nørreå valley and Gudenå valley. As far as can be judged this dry valley was run through by water from north to south at a time when the bottom of the Nørreå valley was situated at least 6 m higher than today, i.e. 9.5 m above sea level. To some extent this corresponds to the terraces at Ålum and to the sand surfaces which are found partly along the sides of the Nørreå valley between Løvskal and Skern Kirke and partly in the connecting valley to the Skalså valley south-west of the threshold of this valley.

Ussing certainly maintains that there are terraces 12-22 m above sea level along the sides of the dry valley. However, visits to the area show that there are no river terraces at this level, but that the western side of the valley is specially influenced by solifluction.

There are several curious circumstances in connection with these systems of valleys. Geophysical-geological investigations (Schrøder 1974) have shown that the dry valley at Langå is found as far down as the pre-Quaternary to a depth of – 20 m, and that the same is the case at any rate with the eastern part of the Nørreå valley, whereas Gudenå valley is not indicated at all in the pre-Quaternary surface. Unfortunately these valleys are mostly outside the examined area, but the pre-Quaternary surface of the area between Langå and Hammel is furrowed by systems of valleys running southeast-northwest. One of these valleys runs under the hill between Torup and Langå at a depth of 60 m. This means that these systems of valleys are older than the last interglacial time for the occurrence of the interglacial diatomaceous earth at Hollerup lies on top of these pre-Quaternary valleys.

The Nørreå valley and the dry valley are old valleys that have been partly filled up. The Nørreå valley was so deep in the post-glacial time that it was a fjord, as marine sediments were found at almost the very western end of the valley (Mentz 1910).

Ussing's Skalså stage, therefore, is a highly dubious stage for which there is no evidence that drainage flowed this way. Indeed, there is much evidence to the contrary. The Gudenå valley is a large and wide valley cut by running water, and this also seems to have been Ussing's opinion; however, the period between the Falborg and Skalså stages is too short for such a large valley to be formed.

As all terraces stop at the bend at Tange, the lower Gudenå valley cannot have existed at the time of the Falborg stage, and the ice border cannot have been far away. The whole Nørreå valley must have been filled with ice at this time, as otherwise the water from the Falborg valley

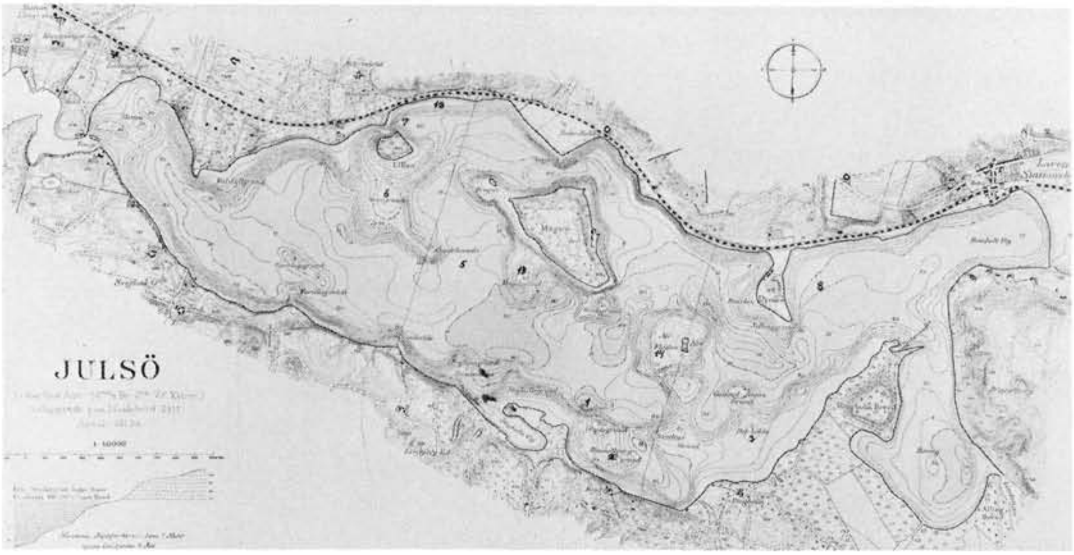


Fig. 3. Map of Julsø. The constant change between islands, shallows and deep holes indicates that buried ice remainders were essential causes of the formation of the lake. The numbers indicate bottom sample stations. Reproduced by Copenhagen University, Geographical Institute, with permission (A 454/72) of the Geodetic Institute.

would have run through it at Rindsholm, where it is united with Vedsø. However, it is impossible to say how the melting of this ice took place, and how the lower Gudenå valley was formed.

The Julsø, Borresø Torså valley

Both Ussing (1907) and Milthers (1948) considered these valleys to be the outer limits of a tunnel valley stretching from Århus through Brabrand Sø and Ravnsø to Knudsø. They considered the glacier cave to have been at Moselund, and the melting water to have shaped the so-called Moselund cone on the Karup outwash plains.

The valley area from Laven to Funder, however, is a considerably more complicated system. At Julsø the width is 1600 m, and from there the valley widens in a funnel shape to the west and northwest to 6 km between the south side of Torsø and the mouth of the Gudenå west of Silkeborg.

The valley area contains a series of lakes, Julsø, Borresø, Brassø, Almind Sø, Thorsø and Silkeborg Langsø.

Silkeborg Langsø is quite shallow with a depth of 4–5 m and a wide flat bottom. Almind Sø has a more uneven bottom relief with three deeps with water depths of 18–20 m separated by thresholds of 15 m water. Brassø forms two basins, one south of Hattenæs across the longitudinal direction of the lake, with 2 m water, and the other one from this point to the narrow passage at Sejs with 14 m water close against the south-western side of the valley. North and northwest of Hattenæs the lake forms two bays with only 2.5 m depth which continue into Almind Sø.

From Svejbæk to Sejs, Borresø forms a basin with depths from 8 to 9 m. Borresø is separated from Brassø by a threshold only 2 m deep, but it also sends a branch direct to the west with depths of about 6 m, enclosing the three "Paradise Islands"; Borre Ø, Langø, and Bredø.

While these lakes have a comparatively even bottom relief, Julsø differs from them in having in its eastern part various deep holes separated by shallows and islands, and thus it is an almost typical example of a bottom-relief caused by the melting of buried ice lumps (fig. 3). The sedi-

Fig. 4. Bottom sample from the Himmelbjerg shallow in Julsø. Quartz grains, calcareous internodes and sporangia from charaphytes and iron oolites. x 12. Halkjer photo.

ments along the coast in depths of water up to 2 m are coarse sand or gravel without any traces of iron, and beyond this limit there is a greyish brown diatomaceous gytje.

On shallow shoals in the body of the lake and around the islands, however, the quartz sands contain numerous iron oolites and internodes of Charaphytes (figs 4 & 5).

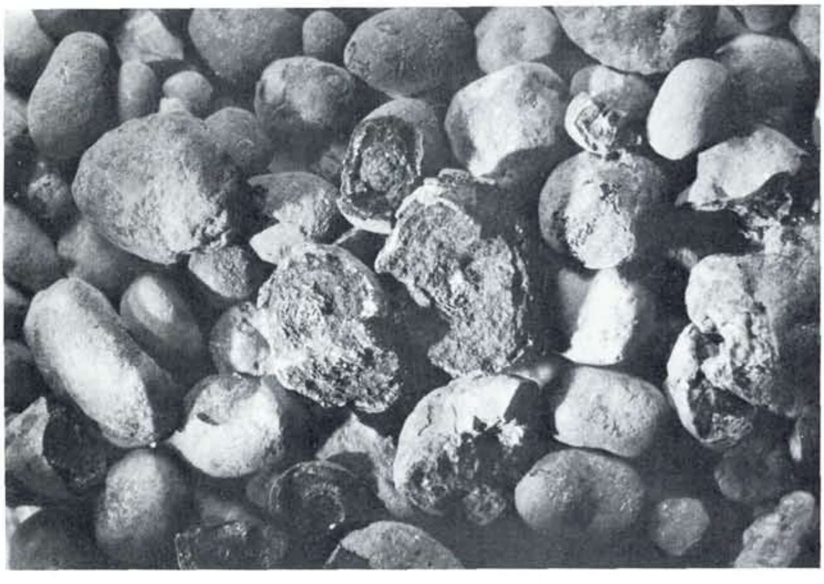


Fig. 5. Iron oolites from the Himmelbjerg shallow in Julsø. x 60. Wolthers photo.

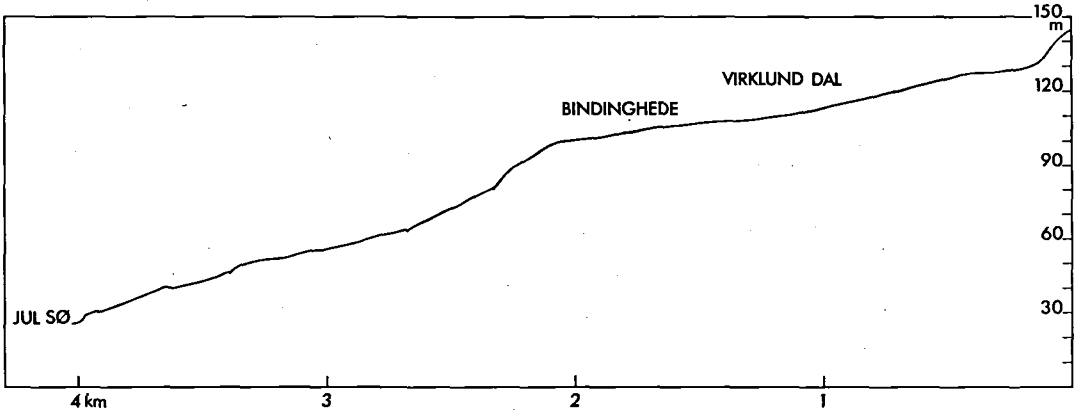


Fig. 6. Longitudinal profile through Virklund valley and Bindinghede. The profile shows how the base of erosion sank stepwise as a consequence of lowering of the ice surface owing to superficial melting.

In Almind Sø the sands and gravels are often cemented by a precipitated ochre, part of which is transported into the lake itself, while another part is precipitated on stones and vegetation along the sides and bottom of the rivulet.

Along the north side of Julsø the high slopes stretch right down to the lake, but from the western end of the lake to Silkeborg there are two terraces in front of the steep slopes.

The uppermost terrace is about 32 m above sea level and can be followed the whole way to Silkeborg. Further on it can be identified as a terrace belonging to the younger phase of the Falborg stage. The terrace forms the river level on which Silkeborg lies and the crescent-shaped plain at the north side of Silkeborg Langsø.

In front of this surface lies the lower terrace, which can be followed – although with interruptions – right into the Gudenå valley below Silkeborg, or at any rate past Sminge.

The south side of the valley has a more complicated form. The side of the valley runs from Birksø to the NW as far as to the south side of Julsø. From Himmelbjerget it bends more to the west along the north side of Limbjerg and Storeknøs, and from here it bends into Stenhule south of Rødkjær to the eastern end of Thorsø, and after that along the south side of this lake and Jenskjær to the Funder valley.

The south side of Julsø is formed by a long area of hills the highest point of which – 157 m above sea level – lies exactly north of the farm Himmelbjerggaard. To the south it is limited by a wide hollow from a hill crest running N–S in Ry Sønderskov, whose west side is furrowed by erosion grooves and which is probably an end moraine (Hansen 1975).

The hill area between Himmelbjerget and Stenhule bears various interesting features. About 400 m NW of Himmelbjerggaarden there is a small lake which forms the uppermost end of Virklund valley. A longitudinal profile through the valley (fig. 6) shows that the first 1.7 km the direction of the valley is SE–NW, and the gradient is 30 m in 2 km = 1 : 66. In front of the outfall of the valley at the farm Bindinghede there is a surface that must be understood as the cone of an outwash plain. The outer edge of the plain lies 100 m above sea level and to the north it is limited by the hill crest Storeknøs whose top is 129 m above sea level (fig. 7). The surface is cut through by Virklund valley, the gradient of which suddely increases to 1 : 20 down to a height of 65 m above sea level, after which the gradient decreases again to 1 : 40 to a height of 50 m above sea level. After a very short distance where the bottom of the valley is again a little steeper, and shortly before the outlet into Julsø it cuts through a terrace the outer edge of which is 32 m above sea level, that corresponds to the upper terrace on the north side of the valley.

It is evident that here a stepwise lowering of the base level of erosion took place as a result of the melting of the ice mass which lay in Julsø.

Fig. 7. View from Storeknøs. To the right Lilleknøs is seen as an isolated hill in the valley. Below the hills the 50 m terrace is seen stretching into the Stenhule valley. Behind it the hill areas around Slåensø. The lake in the background is Julsø.

The 50 m level corresponds to the plain in Stenhule valley to the west.

At the farm Bøgedal a deposit of freshwater marl was found stretching along the wall of the valley to a height of 90 m above sea level. In his diary for 16th June 1879 Johnstrup wrote that here an excellent stratified marl is found containing thin beds of sand deposited during the ice age, owing to an embankment in the valley – either of ice or of sand – that was later washed away. He wondered at the large chalk content, 30.75%, since everywhere the soil was free of calcium carbonate. This marl was still being exploited in 1953 and the section showed stone-free clay with centimetre thick layers of sand; by 1959 the whole occurrence of marl had been dug away.

The curves of the topographical maps clearly show that the northern side of the hill ridge that stretches from Himmelbjerget to the north-west as far as Bindinghede is cut through by long erosion valleys and small terraces showing the

Fig. 8. Gravel pit at Himmelbjerget with stratified terrace gravel.

Fig. 9. Gravel pit at the outlet from Slåensø with moraine gravel.

stepwise lowering of the base level of erosion during the melting of the ice in Julsø, and that this mostly took place from above and downwards and not as a regression of a glacier tongue.

The 50 m level is repeated as terrace plains. Such a surface stretches within Stigsballevig in between Himmlebjerget and the hills about Limbjerg. At the road exactly west of Himmelbjerget there is a terrace 60 m above sea level. A section in the terrace showed uppermost 2.5–3 m stratified gravel-bars and intercallated sand lenses (fig. 8). Under this followed 30 cm fine sand which in turn overlay 30 cm gravel.

From Svejbæk and further to the west several large hill areas are found; Kongestolen 81 m, Åsen 107 m and the hills about Slåensø form a

Fig. 10. The Hummelsø valley seen from north. The chimney in the background is at the dairy at Them.

Fig. 11. The western end of Borresø seen from Freshwater biological Laboratory. In the background the long ridge-like hill Oringen and the innermost Paradisøer.

barrier across the valley. At first glance these would be taken for an endmoraine area analogous with the barriers found in Salten valley (Hansen 1975). Slåensø forms a regular basin with a shallow bottom and a water depth of 10–11 m. The surface of the lake is 24.2 m above sea level, that is 3.5 m higher than Julsø. At the mouth of Slåensø there is a section of very coarse gravel (fig. 9), but at the northern side of the large hill area Lilleknøs there is a section with Tertiary sand, and at Slåensø Tertiary brown coals are exposed in the slope. This indicates that these hills are not end-moraines.

Along the southern side of the Borresø and as far as Virklund the bottom of the valley lies at the same level as the terrace along the northern side of the valley, but also here there are hill ridges reaching into the valley and the "Paradise Islands" in Borresø. Close to the western end of the valley at Virklund a valley stretches towards south-west into Hummelsø north of Them (fig. 10). Its mouth, which is now furrowed by water erosion, originally lay about 50 m above the bottom of the Borresø valley.

Hummelsø lies 77 m above sea level, and to the west of it the large dry valley starts that was mentioned in an earlier work (Hansen 1975). There must once have been a glacier tongue here.

The whole terrain between the western end of Borresø and Brassø has a very rough surface with many small lakes, Ellesø, Marksø, Avnsø and Uglesø, that can only have been produced by melting of buried ice lumps. The two elongated hills Tindberg and Oringen might be suggestive of eskers (fig. 11), but nowhere in them are there any sections giving information of their composition. Morphologically they are of a clearly glacial character, but the large hill area in Vesterskoven, west of this glacial landscape consists of Tertiary material and contains brown coal (Hartz 1909).

Here as in Saltendalen it can be maintained with certainty that the valley area in question (at Julsø, Borresø and Thorsø) is not a tunnel valley carved out by a subglacial melt water river; it is a result of a number of different glacial and periglacial processes and composed of elements from glacial periods older than the latest. Nor is there any direct connection between this valley area and the Moselund cone of the big Karup outwash plains. Between them lies a 15 km wide area characterized by a morphology resulting from a melting period in which the ice cover was gradually reduced and became thinner and thinner. There is no exact cone summit at Moselund, which lies in a depression at the upper end of the valley of Karup Å. Quite considerable quantities of melt-water ran out along the northern side of the valley from the western end of Julsø, having outlet through the upper terrace systems of the Gudenå to the Falborg valley.

The large plain on which Silkeborg lies and the crescent-shaped surface north of Silkeborg Langsø might be regarded as a delta deposit from this river. The question is now how the Langsø

Fig. 12. The Funder valley at Løgagergård. At the railway to the left the valley to Bølling Sø starts. The surface in the foreground is the westernmost part of the Bakkesø. The valley behind it consists of several elongated hills.

arose. As mentioned above, the latter is quite shallow, but still forms a basin so regular that it seems quite improbable that it arose from the melting of buried ice lumps. The Silkeborg lakes, I believe, must be regarded as part of the Funder valley. Ussing (1903) did not write much about this valley, only that the watershed between Limfjorden and Kattegat lies at Bølling Lake 70 m above sea level. From here the Karup Å valley continues southwards with terrace-shaped slopes deeply cut into the moraine landscape towards the Silkeborg lakes.

Milthers (1948) treated the question more thoroughly. He maintained that the highest point of the late glacial Karup Å valley is 82 m above sea level at Løgagergård (fig. 12) and that the valley is a feeding canal to the eastern edge of the plain at a height of 79 m.

The Funder valley may be divided into sevaral differently shaped parts. From Silkeborg to Funder railway town it is 1200 m wide and lies 20 m above sea level, but contains a large and wide hollow and the lake Ørnsø. On its northern side at Lysbro there is a flat hill whose top lies 40 m above sea level. Both in this and similar hills a little more to the south clay was formerly dug for brickmaking, but the clay is mixed with sand and contains discrete beds of sand (Hansen 1940). The remainder of this part of the valley as far as to the continuation of the southern side of the Torsø valley is filled up with various small hills and hollows. Further to the west the Funder valley forms a 400 m wide erosion valley up to Bølling Lake. The length is 3.5 km and the fall 35 m. At the foot of this valley the large dry valley ends that comes from the Hummelsø hollow east of Them. It is not possible to give any unambiguous explanation of the development history of this valley. However, the highly undulating

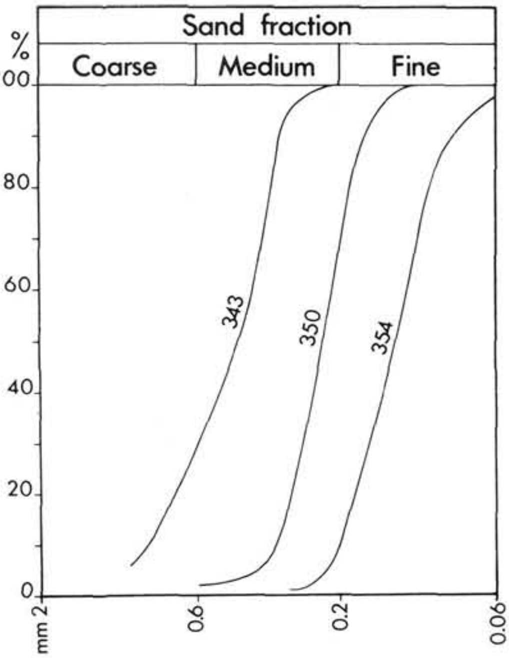


Fig. 13. Granulometric diagram of Tertiary sediments. 343 from the northern side of Lilleknøs. 350 gravel pit at the mouth of Slåensø. 354 the hill along the northern side of Thorsø.

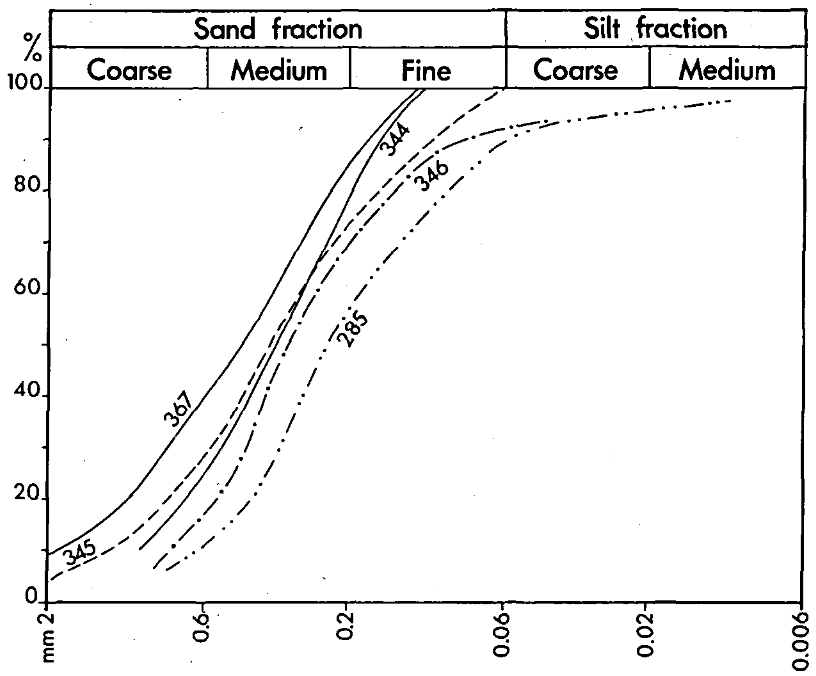


Fig. 14. Granulometric diagram of Quaternary sediments. 245 from the Gudenå terrace north of Caroline Amaliehøj. 344 glaciofluvial gravel at Himmelbjerget. 345 the terrace in front of Lillknøs, beach ridge. 346 the terrace in front of Lilleknøs. 367 the terrace at Hotel Himmelbjerget.

part seems to be a terminal moraine originating from a glacier tongue through the Thorsø valley.

The terrace at Løgagergård which Milters wrote of is no terrace but one of the small hills in this part of the valley. More of these are found just north of this one, all having an elongate form orientated E-W.

The sediments

There are only very few places in the area in question where gravel pits or natural sections are found to show what the hills consist of. But in such places only two kinds of sediments are found. Tertiary sand and glaciofluvial sand and gravel. Figs 13 & 14 show granulometric analyses of these sediments.

The three samples in fig. 13 are Tertiary sand.

Sample no.	M	Q_3	Q_1	So
343	470	660	380	1.31
350	256	280	195	1.20
354	130	170	108	1.26

Thus the Tertiary sand is well sorted with a sorting coefficient ($\sqrt{Q_3/Q_1}$) of about 1.2 – 1.3. Fig. 14 shows the Quaternary sediments.

Sample no.	M	Q_3	Q_1	So
285	230	380	110	1.85
344	340	590	210	1.90
345	310	480	170	1.68
346	340	640	185	1.85
367	420	900	250	1.90

It is evident that the sorting is inferior to that of the Tertiary sand, but also more varied, fluctuating from 1.68 to 1.90.

Conclusions

The result of these examinations must be that Ussing's and Milther's representation of the development of the Gudenå system and the melting of the ice must be considerably revised.

The last glaciations have not had much influence, especially in the Baltic phase. The ice advanced through a landscape that was already modelled with hills, valleys and plains, and several of them were too large for the ice to cause any disturbance or the ice went across them – Gunnar Larsen and his colleagues in Århus showed that as far east as at the Galten-Ølst area there are hills with Tertiary clay that the ice went past. (Larsen et al. 1972). Another area of hills is the large ridge to the south of Mossø containing the highest points of the country, Ejer Bavnehøj and Yding Skovhøj. This area is probably also older than the last glacial time, and must have towered over the ice as a nunatak, but so far, strangely enough, it has not received the attention of geologists. Ussing's Quaternary-geological works are pioneer works inspiring further studies of the shapes of landscapes. Milthers continued these works, but arrived at the conclusion that the indicator boulders and ice-border-lines became panaceas of understanding. Today the problems of Quaternary geology are being attacked from many more different sides. Most important is the Århus geologists' demonstration of foraminifera from the Skærumhede-series in the Weichselian hills. Asger Berthelsen's and his pupils' structure analyses and Johannes Krüger's till fabric analyses are all methods that show new aspects of the Quaternary, but at many places it will also be necessary to analyse the morphology of the landscape. It will be the problem of geologists of the future to coordinate these various methods of examination.

Dansk sammendrag

Gudenå-systemets udviklingshistorie.
I arbejdet gennemføres en kritisk gennemgang af den tidligere litteratur om isens afsmeltning fra hovedstilstandslinien til isens bortsmeltning fra Jylland.

Nye undersøgelser af terrasseniveauerne i de østjyske dalsystemer viser, at Ussing (1904 og 1907) opfattelser af Falborg stadiet er korrekt, og at forklaringen på Skalså stadiet og på isafsmeltningen fra Falborg stadiet til Skalså stadiet behøver fornyede undersøgelser, idet de forklaringer, der hidtil er fremkommet herpå, ikke er holdbare.

Gudenåens søsystemer og de tilgrænsende dales dannelse behøver også nye undersøgelser, idet flere processer med forskellig styrke synes at være ansvarlig for disse erosionsformers fremkomst.

De gennemførte undersøgelser synes at vise, at den sidste isoverskridelse (Baltiske fase) ikke har påvirket områdets morfologi i synderligt omfang, idet landskabets udformning er bestemt af ældre isoverskridelser og de processer der følger med isoverskridelser og isafsmeltning, og det vises, at morfologiske studier, sammen med stratigrafiske og strukturelle undersøgelser, er nyttige og nødvendige, for at opklare det geologiske hændelsesforløb.

References

De Geer, G. 1896: *Om Skandinaviens geografiska utveckling efter Istiden. Stockholms Högskolas* populära Föreläsningar. 160 pp. Stockholm.

Hansen, K. 1971: De Miltherske spaltedale i Jylland. *Dansk geol. Foren., Årsskr. for 1970,* 47–53.

Hansen, K. 1971: Tunnel valleys in Denmark and northern Germany. *Bull. geol. Soc. Denmark* 20: 295–306.

Hansen, K. 1975: The Salten Valley. *Dansk geol. Foren., Årsskr. for 1974,* 5–24.

Hansen, S. 1940: Varvighed i danske og skånske senglaciale aflejringer. *Danmarks geol. Unders.* (2) 63: 478 pp.

Hartz, N. 1909: Bidrag til Danmarks tertiære og diluviale Flora. *Danmarks geol. Unders.* (2) 20: 292 pp.

Hartz, N. & Østrup, E. 1899: Danske diatome-aflejringer og deres diatomer. *Danmarks geol. Unders.* (2) 9: 81 pp.

Larsen, G., Liboriussen, J. & Villumsen, A. 1972: Kvartærgeologiske undersøgelser på kortbladet Randers. *Dansk geol. Foren., Årsskr. for 1971,* 27–40.

Mentz, A. 1910: *Nørreådalens moser og enge.* 55 pp. Viborg: Det danske Hedeselskab.

Milthers, V. 1948: Det danske istidslandskabs terrænformer og deres opståen. *Danmarks geol. Unders.* (3) 28: 233 pp.

Milthers, V. & Westh, T. C. 1913: Viborg Egnens Mergellag. *Danmarks geol. Unders.* (3) 9: 70 pp.

Schrøder, N. 1974: De geofysiske-geologiske undersøgelser af området nord for Århus. *Lab. Geofysik, Aarhus Universitet.* 101 pp.

Ussing, N. V. 1903: Om Jyllands hedesletter og teorien for deres dannelse. *Oversigt kgl. danske Vidensk. Selsk. Forhandl.* 2: 99–164.

Ussing, N. V. 1904: Danmarks geologi. 2. udg. *Danmarks geol. Unders.* (3) 2: 258–267.

Ussing, N. V. 1907: Om floddale og randmoræner i Jylland. *Oversigt kgl. danske Vidensk. Selsk. Forhandl.* 4: 161–213.

Notice to contributors

Two copies of manuscripts, each with a set of illustrations, should be sent to the editor. Articles submitted should not exceed in length 75 000 units of type, equivalent to 15 pages à 4700 units, plus four pages of illustrations. If illustrations cover more than this the text must be reduced accordingly. Longer articles may be published at the discretion of the editor but it is advisable to consult the editor before submitting long manuscripts. Papers will normally be reviewed by two referees and will appear in approximately the order in which they are accepted for publication.

Manuscript

An original and one quality carbon or xerox copy should be submitted. Layout and conventions, particularly in the first page and abstract block, must correspond with those used in the most recent issue of the Bulletin. Leave a wide left margin and double space throughout. Do not use footnotes or appendices. Italics are indicated by underlining with a wavy line. The editor undertakes all other type selections.

The title should be concise and the abstract should not exceed 250 words. The main text is followed by a short summary in Danish. Non-Danish contributors must supply an English summary for translation.

Indicate figure and table placement in pencil in the left margin. Captions must be typed on a separate sheet. Tables are expensive and should be kept to a minimum. References to figures and tables within the text have the form: fig. 1; figs 1,2; table 1. Bibliographic references in the text are given as: Smith (1969:15) and (Smith & Hansen 1970). Where there are three authors or more their names are given in full at the first mention, but subsequently the following form is used: (Smith et al. 1958). In the reference list, references should be abbreviated according to the *International List of Periodical Title Word Abbreviations.* If in doubt, write out the full reference. Authors themselves are responsible for the accuracy and completeness of their references but if an incorrect reference is detected the manuscript will be returned to the author for complete rechecking. The reference list must include all, and only, the references cited in the text of the paper.

Illustrations

All illustrations are termed figures and are printed in their place within the text. Width of figures should ideally correspond either with that of a column (68 mm) or with that of the type area (142 mm). In exceptional circumstances a figure of intermediate width can be accepted, but not in excess of 115 mm wide so as to allow a caption to be placed alongside. Fold-out figures are not accepted. When judging the height of a 'full-page' figure, remember to allow space for a caption below; figure and caption together may not exceed a height of 208 mm. Horizontal illustrations are greatly preferred.

All figures should be submitted as glossy photographic prints (2 copies of each) suitable for direct reproduction, i.e. having the dimensions of the final figure. Do not submit original artwork. Where suitable, scale should be indicated in photographs by a bar, its size given in the caption. Size of smallest letters in illustrations should not be less than 1.5 mm.

It should be borne in mind that during reproduction photographic figures are rephotographed to 102 % to allow for slight masking of all margins. Thus an extremely narrow strip at the edges of the illustration is lost.

Careful attention to the details outlined here will greatly increase the speed with which the manuscript will be processed and published. Page proofs only will be sent to authors and must be returned to the editor within 3 days. The cost of any alterations against the manuscript at this stage will be charged to the author. 50 offprints of each paper are supplied free to authors and additional copies may be purchased in multiples of 50. These should be ordered when returning proofs, stating carefully the addresses to which the offprints and the invoice should be sent.

Contents

ISSN 0011-6297

ANDELSBOGTRYKKERIET
I ODENSE 109 12 10 30