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(A Heavy-Mineral Study)

By
Gunnar Larsen

Dansk sammendrag:
Rhætiske-jurassiske-nedre kretaciske sedimenter
i det Danske Sænkningsområde
(En tungmineral undersøgelse)

I kommission hos
C. A. REITZELS FORLAG (JØRGEN SANDAL)
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ANDELSBOGTRYKKERIET I ODENSE

PREFACE

Knowledge of the deeper part of the Danish underground has developed, as would be expected, simultaneously with the exploration for oil, gas and salt, work that was started by DAPCo (Danish American Prospecting Co.) in 1935. This exploration was interrupted during the Second World War, recommenced in 1946 and finally stopped in 1959 (see ØDUM, 1960; SORGENFREI and BUCH, 1964). Since then oil exploration work has been resumed, this time by DUC (Dansk Undergrunds Consortium).

The geological material that had accumulated in the period up to 1959 was, on the cessation of exploration work by DAPCo, transferred permanently to D.G.U. (Danmarks Geologiske Undersøgelse), and the investigation of this material has been an important task since then. After a somewhat hesistant start, a firm programme of investigation was evolved in 1962, when a research group was set up under the leadership of professor, dr. phil. TH. SORGENFREI. The work of this group came to include geophysical, as well as biostratigraphical and sedimentary-petrographical investigations. The author participated in this team work and was especially concerned with the sedimentological side of the investigations into the geology of the Rhaetic – Jurassic – Lower Cretaceous sediments. The results of this work form the subject of the present paper.

That it has proved possible at this time to bring the research work on the Rhaetic – Jurassic – Lower Cretaceous sediments to a conclusion is due in part to the impetus provided by collaboration with other specialists within the group, and in part to the inspiration given by the leader of the group, professor SORGENFREI. There have been other contributory factors. The author has enjoyed excellent laboratory support in the preparation of the more than 1500 samples examined; in this connection thanks are especially due to hr. EBBE CHRISTENSEN. In addition civilingeniør BIRTHE DINESEN has rendered invaluable assistance by supervising, and to some extent undertaking, the geochemical analyses that have supplemented the petrographical work. The study is based not only on the new analyses but also on the older lithological descriptions to be found in the archives and on the Schlumberger diagrams; the listing of this material from the archives has been predominantly the work of cand. mag. GUNNAR JANSSON. In the account that follows, the diagrams in which the sedimentary analyses are compared with the well sections and Schlumberger logs play a key part. These, as well as the other diagrams, were mainly prepared by fru. RIGMOR BORG. Photographic work was done by hr.

Chr. Westergaard. Mr. G. Henderson translated the manuscript into English.

Thanks are due to those named, as well as to other who, by means of information, or by their comments, or in any other way, have contributed to the accomplishment of the work.

The Danish manuscript was finished in February 1966 and the English one in June 1966.

Gunnar Larsen

CONTENTS

ABSTRACT

The Danish Embayment is a major structural feature in the deeper part of the Danish underground (map, fig. 1). The subject of this study is the Rhaetic, Jurassic and Lower Cretaceous sediments in deep borings in this area. The object of the investigation has been to throw light on the origin of these sediments; the study deals with the lithology and petrography of the beds, and in particular the heavy mineral distribution.

For each boring the observations and analyses have been compiled in the form of a profile diagram (Plates II–XVII); the lithology is shown by means of a columnar section accompanied by descriptions and Schlumberger curves; the analytical data for carbonate content, grain size distribution and also the quantitative mineral distribution in the grain size fraction 75–250 μ are shown alongside.

The Rhaetic, Jurassic and Lower Cretaceous sequence is up to ca. 2 km thick. It consists essentially of rather dark marine clay deposits alternating with lighter, partly non-marine sand deposits. A simplified representation of the distribution of the two main facies in the well section (fig. 3) forms the basis of an account in which the lithological development of the sequence is reviewed. In this account the sequence is subdivided into 11 stratigraphical formations (Table I).

The account of the mineral content of the sediments starts with comments on the various minerals and mineral groups, after which the main features in the mineral distribution are described. In the area examined certain regions can be distinguished whose mineral assemblage does indeed vary upwards through the sequence, but which nevertheless retain their individuality on the whole. The reason for this regional development is discussed. The major differences from region to region are probably due to the sedimentary material having been brought from various areas of denudation; the sediments are evidently mainly derived from Fennoscandia, but the Ringkøbing-Fyn High is also considered to have supplied material. Some of the marked changes in the mineral assemblage are, however, interpreted as being the result of more intense weathering and redeposition of sediments determined by alterations in the palaeogeography of the area. A third controlling factor is diagenesis, which in a few special cases seems to have altered the original mineral assemblage radically.

Finally, the results of the lithological and petrographical investigations are considered collectively in a review of the geological development of the depositional area. This account, which is introduced with comments on the structure of the basin and its relations to the surrounding area, is based on five palaeogeographical maps where the extent of the depositional area, the distribution of the clay and sand facies, and the main features of the heavy-mineral distribution are sketched for the Rhaetic, Lias, Dogger, Malm and Lower Cretaceous respectively. It emerges that considerable changes have taken place in the palaeogeography of the area from time to time. Despite this a certain uniformity can be traced in the sedimentological-palaeogeographical development in the Danish Embayment from the Rhaetic to the close of the Lower Cretaceous; it was first when the widespread Albian marine transgression took place that fundamental changes occurred.

INTRODUCTION

Before DAPCo's exploration work the Senonian chalk and limestone deposits were the oldest strata known in Denmark, excluding the island of Bornholm. The deep wells that have been drilled since then have revealed that the Upper Cretaceous beds rest on a sedimentary sequence that is several kilometres thick and comprises Lower Cretaceous, Jurassic, Triassic and Permian (GREGERSEN and SORGENFREI, 1951; SORGENFREI and BUCH, 1964). It thus appears that Denmark, at any rate since the Permian, has been an integral part of the North European Basin, more precisely of its north-eastern part, bordering Fennoscandia. These features, the fact that it is a part of the North European Basin and the position on the margin of Fennoscandia, are fundamental to the geology of Denmark.

THE DANISH EMBAYMENT

A second important result stemming from the prospecting work has been the recognition that the sedimentary sequence is not uniformly developed throughout the entire area. It is very apparent that the most complete development is to be found in the so-called Danish Embayment (fig. 1). This is an elongated, approximately NW–SE orientated basin or through, which is bounded to the north-east by the Fennoscandian Border Zone and is partly cut off to the south-west from the North German Basin by the Ringkøbing-Fyn High. In the north-west direction, the basin clearly extends for some distance out under the North Sea, while in the south-east direction it obviously joins the Polish Basin.

The depth of this basin is not yet known with certainty, but for the time being can be taken as being about 5 km. The reasons for this estimate are that in the well Gassum 1 the base of the Mesozoic is believed to have been found at a depth of 3.4 km and that the occurrence of a salt dome province with Upper Permian, Zechstein, salt deposits in the north-western part of the basin (ØDUM, 1960; LARSEN, 1963) suggests that there is a considerable thickness of Permian beds under the Mesozoic. In the south-eastern, shallower part of the basin, the well Slagelse 1 encountered older Palaeozoic beds below the Permian (LARSEN and BUCH, 1960; SORGENFREI and BUCH, 1964); whether these particular beds have a more widespread distribution within the basin is as yet unknown. The structural highs, the Fennoscandian Border Zone and the Ringkøbing-Fyn High, which delimit the embayment, are composed of basement complexes of

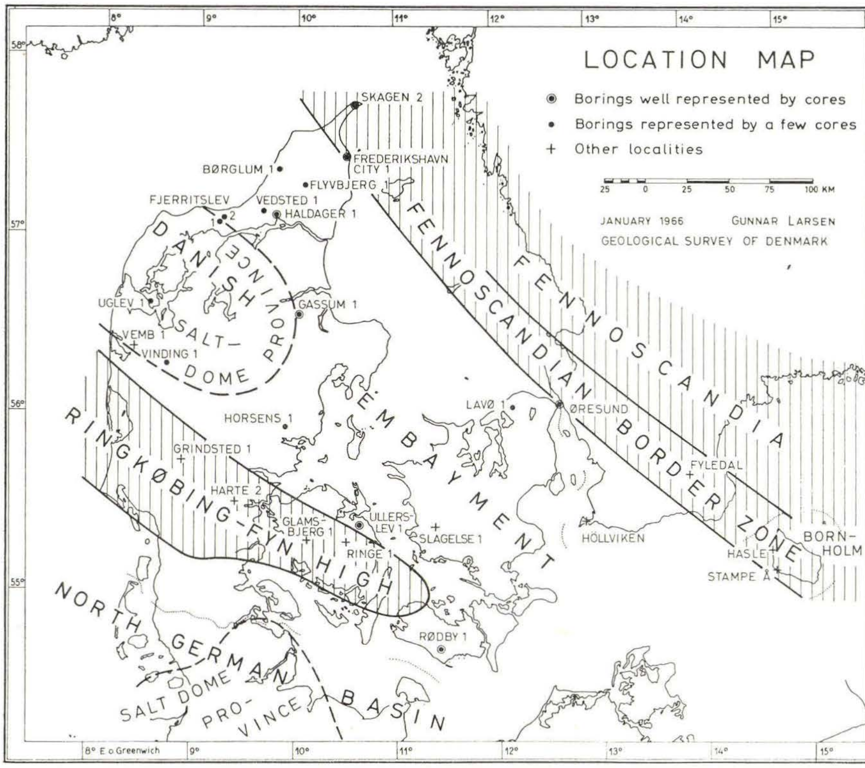


Fig. 1

probable Precambrian age (NOE-NYGAARD, 1951, 1963), covered by a Mesozoic – Cainozoic sedimentary sequence, 1–$1^1/_2$ km thick.

It is not yet possible to state with certainty the age of the Danish Embayment. The fact that below the base of the Zechstein beds in the well Rødby 2 a sequence of rather thick conglomerates and volcanic rocks of probable Lower Permian age was encountered (SORGENFREI, 1957; SORGENFREI and BUCH, 1964) may indicate that there was important tectonic activity during the Lower Permian. Whether or not these events can be connected with the formation of the basin is a problem that must remain unsettled for the time being. It is, however, abundantly clear that the Danish Embayment had already come into being when the Upper Permian salt deposits were formed, and furthermore that the character of the area of subsidence played an influential part throughout the Mesozoic until the Upper Cretaceous. In the Upper Cretaceous there was less difference between the sedimentary development in the basin and that in the area above the structural high. The Danish Embayment thus appears to have lost the character of an independent depositional area towards the close of the Mesozoic.

RHAETIC - JURASSIC - LOWER CRETACEOUS

The rock sequence filling the basin can be characterized briefly as follows.

The Upper Permian evaporites are overlain by a Triassic succession, more than 1,5 km thick (SORGENFREI, 1965, fig. 3), consisting of reddish to red-green variegated sandstone and claystone, in which there are scattered occurrences of $CaSO_4$ and in a few places layers of rock salt (Gassum 1). At the same time as these sediments were being laid down there was clearly being formed along the edge of the basin a marginal facies of reddish and greenish, rather coarse arkoses (wells Skagen 2, Frederikshavn City 1). A comparable border facies is also known in Skåne, under the name Kågeröd Formation (TROEDSSON, 1942; BROTZEN, 1950).

The youngest part of the Triassic succession, the Rhaetic, is lithologically quite different from the rocks lying below, and can instead be grouped with the succeeding Jurassic formations, in that it consists of an alternating series of light sandstones and dark claystones containing plant material, including occurrences of coal, as well as marine fossils in places. The same lithological development is found in the rocks immediately above the Jurassic, the Lower Cretaceous beds.

In marked contrast, the Upper Cretaceous strata consist of predominantly light grey to whitish marl and limestone deposits.

It can be seen from the foregoing that the Rhaetic - Jurassic - Lower Cretaceous succession in the Danish Embayment occurs as a lithological and lithogenetic unit, which stands out clearly from both the underlying variegated Triassic sequence and the succeeding whitish calcareous formations. However, this can be a little misleading since the boundary between the calcareous and the terrigenous sediments does not coincide everywhere with the boundary between the Upper and the Lower Cretaceous.

In north Jylland (Jutland), for example in the well Frederikshavn City 1, the boundary is found in the lower part of the Upper Cretaceous, at a level provisionally determined as being the transition from Cenomanian to Turonian. Farther south, for example in the wells Vinding 1 and Rødby 1, the boundary lies stratigraphically deeper, the upper part of the Lower Cretaceous, to be precise the Albian, being developed as a reddish marl or limestone. Thus the boundary between the calcareous sediments and the terrigenous sediments is clearly a facies boundary, which behaves "transgressively" in relation to the chronostratigraphical sequence.

The Rhaetic, Jurassic and Lower Cretaceous have, as indicated, been dealt with in several publications. The general features of the lithology and stratigraphy have been described by GREGERSEN and SORGENFREI (1951) and SORGENFREI and BUCH (1964); also DINESEN (1960) may be mentioned here. NØRVANG (1946, 1957) has given an account of the foraminiferal fauna in the Lower Jurassic (Lias), and BRUUN CHRISTENSEN (1962) a description of the ostracod fauna in certain Rhaetic occurrences. Some features of the petrography of the beds are discussed by LARSEN (1964). Finally SORGENFREI (1964), in a series of lithofacies maps, has sketched the palaeogeographical development. It is also appropriate to mention SKEAT and MADSEN (1898), who described fossiliferous Jurassic and Lower Cretaceous blocks from the Quaternary of north Jylland. These blocks probably came from the beds along the north edge of the Danish Embayment (ROSENKRANTZ, 1939).

PURPOSE AND SCOPE OF THE SEDIMENTARY INVESTIGATIONS

In the preceding section a general account has been given of the pre-existing knowledge of the Rhaetic – Jurassic – Lower Cretaceous sediments in the Danish Embayment, and the sedimentary investigations described here must be seen in the light of this.

The reason for starting these investigations was to find out more about the history of the sedimentation, including the conditions in the area of sedimentation and the transport of material. The main emphasis has been placed on a quantitative analysis of the mineral content of the sediments, in particular of the heavy-mineral content. This was done because it was believed from the outset that there might be an opportunity of finding in the heavy-mineral assemblage evidence reflecting the character of the denudation area, and possible changes in the direction from which the material came. The study has not been all-embracing; for example, it has not included the finest-grained fractions, for instance, the clay fraction. On the other hand the study can not as a whole be described as specialized since it has been attempted to portray the specialized part of it, i.e. the analysis of the mineral content, against the background of the general lithology and stratigraphy.

From the geographical point of view the study has been especially concentrated on wells in the Danish Embayment, but in addition some boreholes situated on the adjacent structural highs, the Fennoscandian Border Zone and the Ringkøbing-Fyn High, have been included in the study. On the other hand wells south of the Ringkøbing-Fyn High, i.e. the boreholes in south Jylland have not been included in the study.

The Danish Embayment also includes parts of Skåne (Scania); the Fennoscandian Border Zone cuts across Skåne and encompasses Bornholm. It would therefore be natural to consider the Jurassic beds of Skåne and Bornholm along with the sections investigated in this study. It has been possible to do this to some extent in the case of Skåne by incorporating the results of an earlier study of the Jurassic in the northern Øresund area (LARSEN et al., 1965) in the present work. It must be mentioned here that knowledge of the Jurassic succession in the Øresund region is incomplete; however, the part of the succession that is known seems to be representative of the Jurassic of Skåne. On the other hand, it has not been possible to take Bornholm into consideration to any extent in this study, because, amongst other reasons, there are only a few heavy-mineral analyses from the Jurassic of Bornholm to be found in the literature (e.g. WEYL and WERNER, 1952).

MATERIALS AND METHODS

MATERIALS USED

As already mentioned, the study has covered a number of wells that have been drilled into, or through, the Rhaetic – Jurassic – Lower Cretaceous sediments. In some of the boreholes the entire succession is represented, in others only a part.

The sample material available falls into two groups, core samples and ditch samples. Certain of the wells are represented by an almost continuous series of cores; others have only been cored in particular intervals, while a very few were only drilled and not cored throughout the whole of the stratigraphical sequence under consideration. Core samples are of course excellent material for detailed petrographical and other analyses. Ditch samples, on the other hand, are almost worthless in this respect since the contamination, which must be taken into account, by material falling down the hole, makes it extremely difficult to interpret any analytical data with reliability.

During this study the petrographical analyses of the mineral content were therefore made exclusively on core samples. For this purpose more than 1500 samples were taken for analysis from the core material.

Even if ditch samples are considered to be unsuitable for detailed petrographical studies, they can nevertheless be used, for want of better, to furnish information on the general lithological features of the succession; this is particularly the case where evidence from the ditch samples can be compared with the results of Schlumberger measurements in the borehole (LEROY, 1951, pp. 344–503). Schlumberger diagrams are available from nearly all the wells under consideration. In sections that have not been cored, the descriptions of the ditch samples and the information from the Schlumberger diagrams have been used as a basis for assessing the lithology.

As will be clear from what has been mentioned, the wells under consideration provide study material of very varying quality. Fig. 1 is a map showing the area of the investigation, with the positions of the borings. Symbols have been used to differentiate between borings from which there are 1) no petrographical analyses, 2) petrographical analyses of sporadic core samples and 3) petrographical analyses of core sequences representing an important part of the section.

TREATMENT OF THE SAMPLE MATERIAL

The wells have been investigated lithologically, geochemically and petrographically.

Lithological investigation

The lithology of sections that were not cored was, as mentioned earlier, assessed on the basis of evidence from cuttings and by examination of the Schlumberger profiles, especially the S.P. and resistivity curves, but also in some cases the gamma-ray curves. During this assessment no new examination of the ditch samples was made; the field-geological descriptions in the archives were used.

In cored intervals, when the samples were being selected from the cores a new investigation was made. This consisted of a macroscopical examination of the cores; the rock type, colour, grain size, texture and structure were described.

The samples for analysis were examined in various ways as described in the following.

Carbonate determination

The content of carbonate in the samples was determined chemically, using two different methods. The first of these was the titration method, in which the carbonate content is calculated from the amount of acid used up when the sample is boiled with a known quantity of 0.5 N HCl, the amount of acid left being determined by titration with 0.5 N NaOH. In the investigation of material containing acid-soluble iron compounds the titration method is unsuitable, and instead of this the CO_2-absorption method was used. The principle behind this is that CO_2 is driven out of the sample using HCl and absorbed in a special tube. The amount of CO_2 absorbed is determined by weighing, and the carbonate content of the sample is thereafter calculated. As mentioned earlier, these analyses were supervised by civilingeniør BIRTHE DINESEN.

Preparation for petrographical analysis

It was stated previously that the aim of the investigation was to determine the mineral content, in particular the content of heavy minerals, in the samples being analysed. After consultation with statsgeolog dr. phil. HELGE GRY, it was decided to make the investigations on the fraction with grain size from 75 μ to 250 μ. The procedure used for preparation was not essentially different from that used previously by the author (LARSEN and DINESEN, 1959) and was as follows.

The sample was first examined macroscopically, and the rock type, colour, grain size, texture and structure were described. In determining the colour the "Rock-Color Chart" (GODDARD et al., 1948) was used.

The sample was thereafter divided, one part being retained as reference material, the other being used for analysis. This part was first weighed and then divided into three fractions by wet-sieving using sieves with mesh size 75 μ and 250 μ respectively. The fractions 75–250 μ and > 250 μ were then dried and weighed. The fraction < 75 μ was not collected, but its weight was determined as the difference between the weight of the whole sample and the weight of the two fractions that were collected. The amounts of the three fractions were then calculated in per cent. The results arrived at for grain size distribution are of course subject to some degree of uncertainty since the amount of one fraction (< 75 μ) was not determined directly. In a number of cases the sample of the sediment was so indurated that crushing or acid treatment had to be used before separation into fractions.

Further investigations concerned the 75–250 μ fraction only. After weighing, this was treated with acid, firstly with warm 5% HCl to remove any carbonate, and thereafter with warm 15% HCl to remove any film of iron compounds on the grain surfaces.

After acid treatment, the material was washed, dried and weighed and was then ready for separation using a heavy liquid. Bromoform (sp. gr. 2.87) was used for this purpose and alcohol was used as rinsing agent. After rinsing and drying, the light and the heavy fractions were weighed and the weight distribution calculated in per cent.

Then followed the last phase in this preliminary work, the production of the microscope preparations. Two preparations were made from the light fraction of each sample using Canada balsam (n ∼ 1.54) as the mounting medium. Three preparations were made from the heavy fractions, one being mounted in Canada balsam and two in Clearax (n ∼ 1.666).

Petrographical analysis

The finished preparations were examined with the aid of a polarizing microscope in order to identify the mineral components. To assist in this work, material for comparison in the form of standard collections of different minerals, and various reference books, e.g. MILNER (1952), MILNER et al. (1962) and KRUMBEIN and PETTIJOHN (1938) were used.

After identification of the components their relative amounts were determined by grain counting. In this operation the preparation was moved with the aid of a mechanical stage. With normal counting, only the grains passing the intersection of the cross-hairs during travel of the preparation were counted. In special counts of components occurring in very small amounts, all grains in the preparation were counted where this was necessary for calculating the percentage.

The percentage distribution of components in the light fraction was determined after counting 100 grains: glauconite, fossil remains, plant remains, various other aggregates and allochthonous grains (i.e. mica, quartz, feldspar). After this the counting of the allochthonous components was continued. The mica content was expressed in per cent after counting 100 allochthonous grains, and the relative amounts of quartz and feldspar were expressed by the quotient quartz/feldspar after counting 100 grains of quartz and feldspar.

The counting of the heavy fraction was likewise done in three stages. Firstly the percentage distribution of the following components was determined: pyritized fossil remains, other opaque material and non-opaque components. After this the counting was done on the non-opaque minerals only. As with the light fraction, the mica content was calculated after counting 100 grains. The percentage distribution of the other non-opaque minerals was arrived at after counting 200 of these minerals. The reason for counting twice as many grains as in the other groups was partly that most importance was attached to the minerals in this group in the present study and partly that this group contains a greater variety of minerals than the groups mentioned previously. In the heavy fraction there were a few minerals (e.g. barytes, siderite, phosphorite) whose presence was registered but whose amount was not determined.

In certain parts of the well sections the amount of the non-opaque heavy minerals was so low that it was not possible to give a percentage distribution for the individual samples. Where feasible, the percentage calculation in such a case was based on the sum of the counting values from two or more neighbouring samples. A similar method was used in some cases for calculating the ratio quartz/feldspar in the light fraction.

The information obtained from these countings was tabulated and thereafter plotted graphically.

These systematic investigations were, in a few cases, supplemented by other investigations, namely, chemical analysis of glauconite and other components in the light fraction, and thin-section examination of certain indurated sedimentary bands.

PRESENTATION OF THE RESULTS OF THE ANALYSES

15 deep wells were investigated altogether according to the procedure described in the previous section. The results from each boring have been compiled in the form of a profile diagram. These results are shown in the accompanying plates II–XVI, and are based on the following wells.

Skagen 2	Plate	II
Frederikshavn City 1	–	III
Børglum 1	–	IV
Flyvbjerg 1	–	V
Haldager 1	–	VI
Vedsted 1	–	VII
Fjerritslev 1	–	VIII
Fjerritslev 2	–	IX
Uglev 2	–	X
Vinding 1	–	XI
Gassum 1	–	XII
Horsens 1	–	XIII
Ullerslev 1	–	XIV
Rødby 1	–	XV
Lavø 1	–	XVI

These are supplemented by Plate XVII, which is a compilation of comparable data from borings investigated earlier in the Øresund area (LARSEN et al., 1965). The legend for the profile diagrams is given in Plate I.

The following comments will be made about the diagrams. The starting point is the lithological section, in which the main features of the lithology of the sequence are shown by means of symbols. It must be emphasized that this column is generalized since the scale used did not allow a detailed representation of the lithology. In connection with the section there are two depth scales, the one on the right giving depth (in metres or feet) below the drilling platform, and that on the left giving depth (in metres) below the surface of the terrain. The height of the terrain above sea level at the various localities is as follows.

Skagen 2	1,8 m
Frederikshavn City 1	9,5 m
Børglum 1	19,2 m
Flyvbjerg 1	44,1 m
Haldager 1	1,8 m
Vedsted 1	2,0 m
Fjerritslev 1	4,5 m
Fjerritslev 2	4,5 m
Uglev 1	32,3 m
Vinding 1	56,7 m
Gassum 1	53,5 m
Horsens 1	53,5 m
Ullerslev 1	22,0 m
Rødby 1	2,1 m
Lavø 1	25,0 m

Immediately to the right of the lithological column the intervals cored are marked. Core recovery is shown in black. In cases where the core recovery was less than 100% the symbol for core recovery has been placed in the upper part of the cored interval since it is considered that incomplete core recovery in most cases is due to the loss of the lower part of the core in the hole. One of the reasons for giving this information has been to show in which parts of the well section assessment of the lithology is based on a good knowledge of the material.

The section is accompanied by Schlumberger diagrams and descriptions. The Schlumberger diagrams are placed in the usual manner, i.e. with the resistivity curves on the right of the section and the S.P. curve on the left. In those cases where there is a gamma-ray curve, this is placed to the left of the S.P. curve. The scales for these curves are placed at the top. As mentioned earlier, these curves were used to assess the lithology in sections that were not cored.

The description accompanying the section is on the left of the section. It is, as can be seen, a summary description. In the section that has not been cored it corresponds approximately to present knowledge of the nature of the material, while in the cored interval it is merely a brief résumé of much more detailed observations.

The stratigraphical assessment is given on the extreme left of the diagram. This is based exclusively on available literature on the subject, especially NØRVANG (1957) and SORGENFREI and BUCH (1964). It should be noted that the stratigraphical assessment is still of a provisional nature, and that the biostratigraphical investigations currently being made in the D.G.U. research group will lead to certain revisions of the stratigraphical subdivision of the succession.

The data mentioned may be regarded as material of a general nature. The results of the special petrographical investigations are given in a number of diagrams to the right of the well section with its accompanying Schlumberger curves.

First comes a plot of the position, in relation to the well section, of the samples analysed; the sample number is also given here.

Then follows a description of the colour of the samples examined. As stated, the determination of the colour was based on a special colour chart and formed part of the initial treatment of the sample. The diagram gives a simplified, schematic representation of these observations. It has been arranged so that the predominating colour of the sample is indicated with a solid line, while the subsidiary colour or colours are shown with a dotted line; for example, the symbol for the colour "light olive grey" consists of a solid line in the column "light grey" and dotted lines in the columns "green" and "brown". The purpose of this diagram has been to bring out the essential features of the detailed observations. It must be noted that the samples were examined when they were dry. The colours registered must therefore be considered to be somewhat ligther than they would have been if the samples had been examined in their original, moist condition.

The next diagram shows the results of the carbonate determinations. Closer determination of the carbonates was not undertaken, but it is considered likely that $CaCO_3$ is a prominent component and that $FeCO_3$ plays an important part at certain levels.

The next diagram shows the grain size distribution. As mentioned, a determination of the relative amounts of the fractions < 75 μ, 75–250 μ and > 250 μ was made in connection with the preparation of the samples. The results of these determinations are shown in the diagram. It is clear that this is not a detailed account of the grain size distribution. In fact, the diagram only shows whether the samples are predominantly fine-grained, medium-grained or coarse-grained. It should be noted that in cases where crushing or acid treatment had to be undertaken before fractionizing, the result of fractionizing has not been included in this diagram. In the well Lavø 1 (Plate XVI) all the samples were so indurated that crushing was necessary for the preparation. The diagram "grain size distribution" has therefore been totally omitted for this boring.

All the following diagrams concern the mineral content in the grain size fraction 75–250 μ. The first of these shows the main components of the light fraction. The distribution of the components has been arranged in such a manner that the glauconite and the fossil remains, which with some reservations can be taken as indicators of a marine environment, are depicted on the left side of the diagram, while the plant remains, which presumably belong mainly to a non-marine environment, are depicted on the right side. The intervening part of the diagram shows the relative amounts of the following components: various aggregates, mica, and quartz + feldspar. No further importance is attached to these in assessing the environmental conditions.

The next diagram shows a special feature of the light, allochthonous material, the proportion quartz/feldspar. It is common knowledge that this particular ratio, quartz/feldspar, is used to express the maturity of a sandy sediment (see

Pettijohn, 1957). In this connection it should be recalled that an arkose is defined as a sandstone with a feldspar content of 25% or more or, expressed in another way, with a quartz/feldspar ratio of 3 or less. For use in converting the ratio quartz/feldspar to the amount of feldspar as a percentage of the total quartz + feldspar (and vice versa), the accompanying fig. 2 has been produced.

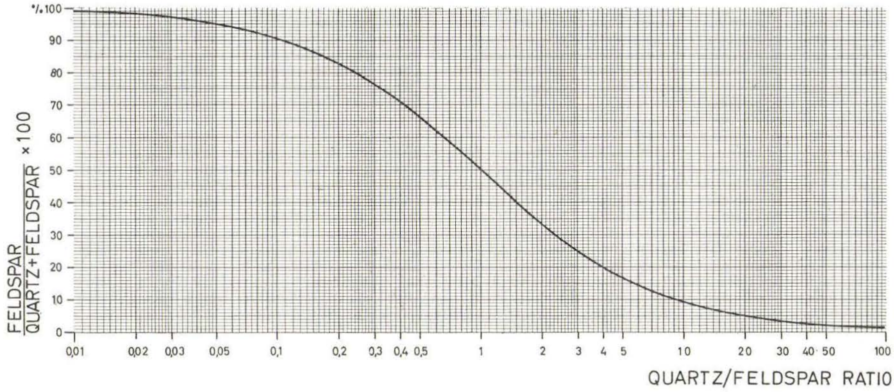


Fig. 2. Conversion diagram for quartz/feldspar ratio ⇄ % feldspar in total quartz + feldspar.

In the next diagram the main components of the heavy fraction are shown, i.e. the relative amounts of the four groups: pyritized fossil remains, other opaque material, mica and other non-opaque grains. Like the glauconite grains and fossil remains in the light fraction, the first of these four groups is regarded as being an indicator of marine depositional conditions. The other three main components are not really of use in making such an interpretation.

As mentioned, the present study has been concentrated especially on the non-opaque, non-micaceous heavy minerals; it is these minerals that are dealt with in the remaining part of the profile diagram. For each mineral or mineral group there is a diagram giving the amount in per cent. In some cases the presence of the minerals is merely marked with a +. This indicates samples in which the number of grains was too small for calculation of the percentage. The order in which the minerals are indicated has been chosen on the basis of a rough evaluation of the resistance of the minerals to chemical alteration; the minerals farthest to the left are considered to be the most stable and those to the right the least stable (see Weyl, 1952). Finally in the section "Remarks" the occurrence of various minerals not included in the quantitative investigation is recorded.

This presentation of the results of the analyses can be regarded as an introduction to the following two sections dealing with, respectively, the lithology and the mineral content of the Rhaetic – Jurassic – Lower Cretaceous sequence.

LITHOLOGY AND STRATIGRAPHY

MAIN FEATURES

The Rhaetic–Jurassic–Lower Cretaceous sequence is built up essentially of sand, silt and clay; there are in addition subordinate amounts of coal, limestone and clay-ironstone.

When the columnar sections are studied in detail it can be seen that the three major components alternate strongly. If, on the other hand, the sections are considered in a more general way, it can be seen that the individual sections can be subdivided into certain large units, which are predominantly sand-silt or clay-silt. The results of such a subdivision of the sections are given in fig. 3. The well sections have been arranged here in three lines, one to the west, one in the middle and one to the east, the lines being orientated more or less at right angles to the edge of the basin. In the figure, the lines have been placed one above the other, so that the western line is at the top and the eastern line at the bottom. It should be noted that the well Vedsted 1 is common to both the western line and the middle line, which fact has determined the relative positions of the two lines in the figure. Finally, the eastern line has been arranged in such a manner that the locality that obviously has the thickest sequence of beds (Øresund) is placed below the places in the other two lines where the thickness of the Rhaetic – Jurassic – Lower Cretaceous is greatest. The correlation lines for the major chronostratigraphical units (Rhaetic, Lias, Dogger, Malm, Lower Cretaceous) have been drawn on the sections.

The figure illustrates the already well known fact (see SORGENFREI, 1963), that the most complete stratigraphical sequence is to be found in northern Jylland (Vendsyssel, Limfjord area), while the other parts of the area of sedimentation lack one or more of the major stratigraphical sections. It is moreover apparent that in this north Jylland area, where the sequence is best developed, the succession can be subdivided lithologically into three main sedimentary cycles, each consisting of a lower, predominantly sand-silt phase and an upper, predominantly clay-silt phase. If a restricted part of north Jylland is considered, namely the area Frederikshavn – Børglum, it can be seen that in the first cycle the sand phase is of Rhaetic age and the clay phase of Lower Jurassic (Lias) age. The second cycle comprises Dogger sand and Lower Malm clay. In the third cycle the sand sequence belongs to the Upper Malm and the basal part of the Lower Cretaceous, while the clay sequence comprises the remainder of the Lower Cretaceous.

The relation between chronostratigraphy and development of sedimentation outlined here applies, as mentioned, to a restricted part of the north Jylland area. If the development is followed out into the deeper part of the basin (Vedsted – Fjerritslev) it can be seen that not only do the sandy sections become thinner while the clayey sections increase in thickness, but also that the po-

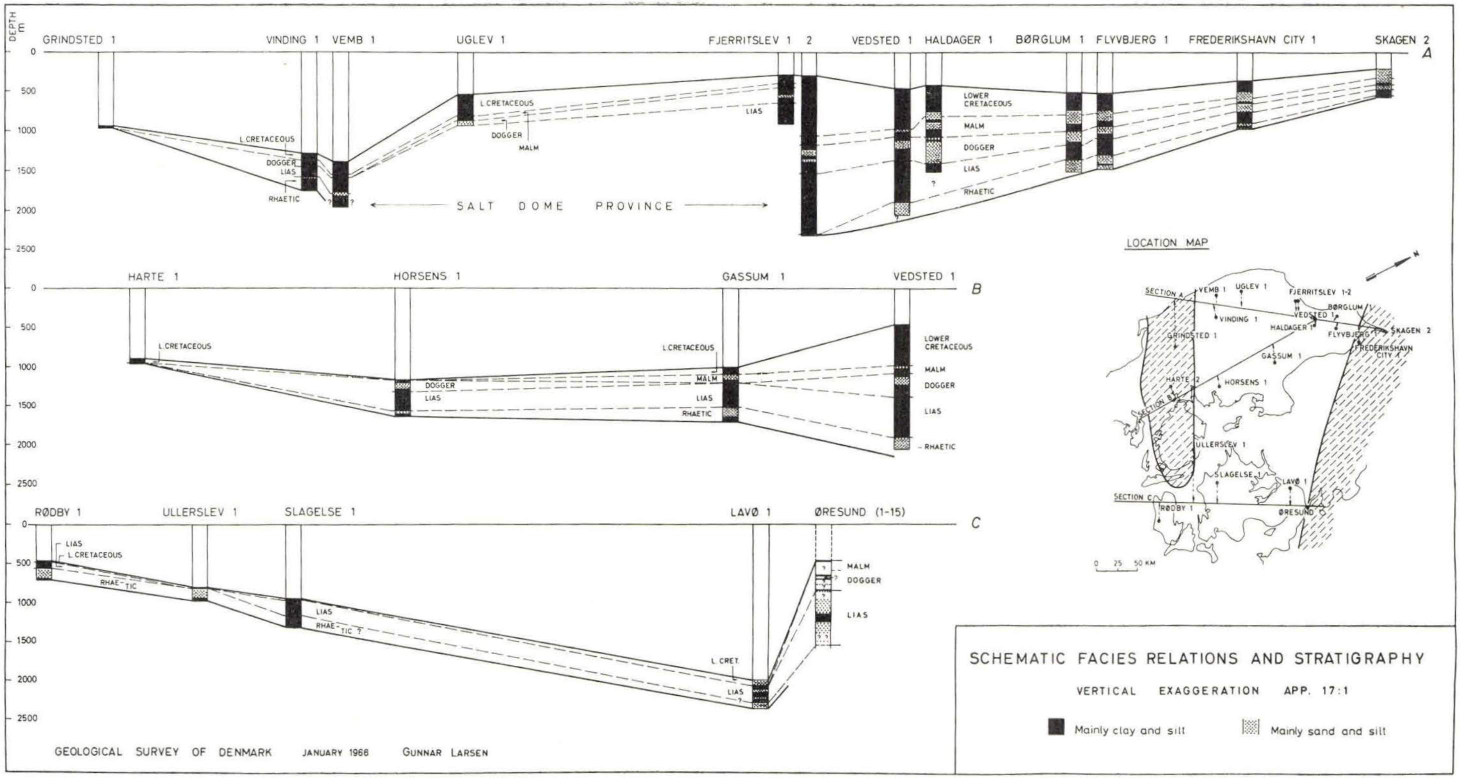

DEPTH m
GRINDSTED 1
VINDING 1
VEMB 1
UGLEV 1
FJERRITSLEV 1 2
VEDSTED 1
HALDAGER 1
BØRGLUM 1
FLYVBJERG 1
FREDERIKSHAVN CITY 1
SKAGEN 2
A
L.CRETACEOUS
DOGGER
MALM
LIAS
RHAETIC
LOWER CRETACEOUS
SALT DOME PROVINCE
HARTE 1
HORSENS 1
GASSUM 1
VEDSTED 1
B
RØDBY 1
ULLERSLEV 1
SLAGELSE 1
LAVØ 1
ØRESUND (1-15)
C
L. CRET.
LOCATION MAP
SECTION A
SECTION B
SECTION C
0 25 50 KM
GEOLOGICAL SURVEY OF DENMARK
JANUARY 1966
GUNNAR LARSEN
SCHEMATIC FACIES RELATIONS AND STRATIGRAPHY
VERTICAL EXAGGERATION APP. 17:1
Mainly clay and silt
Mainly sand and silt

Fig. 3.

sitions of the cycle boundaries in relation to the chronostratigraphical boundaries change. As a natural consequence of this, in the following investigation of the nature of the sequence it has been attempted to distinguish between chronostratigraphy and lithostratigraphy (see HEDBERG, 1954; also KRUMBEIN and SLOSS, 1963, pp. 8–52; TROELSEN and SORGENFREI, 1956).

It should be noted that, in the Øresund occurrence, a subdivision of the Jurassic into lithostratigraphical formations has already been made (LARSEN et al., 1965); the results of this subdivision are shown in Plate XVII. This subdivision into formations was to some extent made on the basis of pre-existing nomenclature for the Jurassic of Skåne (TROEDSSON, 1951; BÖLAU, 1954, 1959). As is known, the establishment of a lithostratigraphical formation requires that, in terms of geographical extent, it should occur as a unit. When certain major features in the development of the beds are considered, the Øresund occurrence obviously shows some similarity to the succession in the rest of the Danish Embayment; however, it is so individual and divergent in some respects that, for the time being, it has not been found advisable to apply the formation names from the Øresund occurrence to the remainder of the basin. It is for this reason that some new lithostratigraphical formation names have been introduced in the following account in which the succession is examined in chronostratigraphical order.

RHAETIC

The strata underlying the Rhaetic beds seem to consist everywhere of rather lime-rich Keuper claystone or marl with a greenish colour that becomes brownish downwards. In the upper part there are usually some plant remains, while in a few places, such as in Ullerslev 1, an ostracod fauna occurs (CHRISTENSEN, 1962).

As mentioned, the Rhaetic in north Jylland is developed as a predominantly sandy facies. This sandy unit extends as a more or less lenticular body from the Frederikshavn area southwards to include Flyvbjerg, Børglum, Vedsted and Gassum; the occurrence at Horsens may also belong to this unit. It thins out westwards between Vedsted and Fjerritslev. This occurrence seems so well defined, both lithologically and in terms of geographical extent, that it seemed reasonable to consider it as a formation. It has been called the *Gassum Formation* after the locality Gassum, where the sediments are rather well developed and also represented by a reasonable amount of core material. The Gassum Formation is a predominantly light grey to whitish, in places rather coarse-grained sandstone, sometimes resembling an arkose, with subordinate dark-coloured clay bands and coal lenses; fragments of coalified wood together with remains of leaves etc. (fig. 6) appear here and there. In a few places a sparse microfossil content is found. Where sand and clay alternate in thin beds, lenticular and crumpled bedding can be seen now and then; since the deformed zones appear

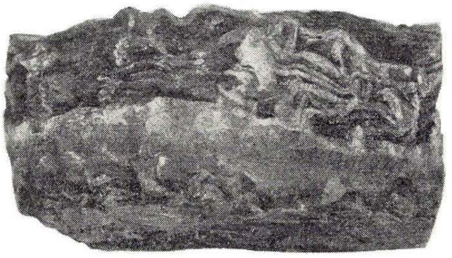


Fig. 4. Rødby 1; section of the core 2330′–2342′; Rhaetic-Keuper; marl with limestone band a few millimetres thick showing cone-in-cone structure. $\times {}^2/_3$.

Fig. 5. Rødby 1; section of the core 2301′–2314′; Rhaetic; oolitic clay-ironstone concretion with septarian structure. $\times {}^2/_3$.

Fig. 6. Vedsted 1; cross section of the core 2006–2012 m; Rhaetic; claystone with carbonized plant material (*Cladophlebis* sp.). $\times {}^2/_3$.

to be bounded by obviously undisturbed layers, the deformation may be classified as synsedimentary, probably belonging to the phenomenon slumping (see HADDING, 1931; POTTER and PETTIJOHN, 1963). In a few cores there are vertical, straight, sand-filled tubes, some of which may be due to burrowing mussels, while others are obviously the work of worms (see GOLDRING, 1964). The lithology, extent and form of the formation suggest that it is of deltaic origin and spread out into the basin from a source in the north or north-east.

At Vinding, in the south-western part of the basin, the Rhaetic is developed as dark grey to almost black clays about 180 m thick, in which subordinate, very thin sandstone bands occur. This development is clearly marine as shown by the content of both molluscs and microfossils. Very little is known about the geographical extent of this particular development. In the nearby boring Vemb 1 an evidently non-marine deposit has been attributed with some uncertainty to the Rhaetic, but since there are no cores from this well, the relation to the Vinding occurrence can not be regarded as having been settled satisfactorily. Until now there has not been any definite information about Rhaetic occurrences in the salt dome area that separates Vinding from the localities Fjerritslev, Vedsted and Gassum. The isolated occurrence of marine Rhaetic at Vinding is called the *Vinding Formation* in the following account. It is possible that the clayey beds forming the base of the Gassum Formation in Horsens 1 and Gassum 1 should really be assigned to the Vinding Formation, but this question can only be settled after further, more detailed studies.

In the well Ullerslev 1, on the boundary between the basin and the Ringkøbing-Fyn High, the Rhaetic is present as a ca. 120 m thick section of fine-grained greyish sand passing down into a dark-coloured clay; this, in turn, seems to pass down with relatively smooth transition into the underlying greenish Keuper clay with plant remains. The Rhaetic beds contain plant remains, and an ostracod content has been found in the clays (CHRISTENSEN, 1962). In the sand beds cross-bedding is met with in places, and disturbances of the attitude of the bedding, attributed to slumping phenomena, occur locally. Clay-ironstone is present in the form of concretions, some of which show septarian structure. An almost identical sand sequence with underlying clay was encountered in the well Rødby 1, which is also situated in the neighbourhood of the Ringkøbing-Fyn High, to be precise at its south-eastern end, where the Danish Embayment is connected with the basin to the south. The sand sequence in Rødby 1 seems however to contain more thin, dark-coloured clay bands than does the sand in Ullerslev 1. Where sand and clay alternate in thin layers, there are often lenticular and crumpled structures visible, which probably originated by slumping. Cross-bedding has been seen in several places (see fig. 8). As in Ullerslev 1, there is plant material in the sand beds, while the clays contain ostracods. Both sections obviously represent the Rhaetic border facies along the Ringkøbing-Fyn High, which existed during that period as a land area (SORGENFREI, 1963). It has been assumed that

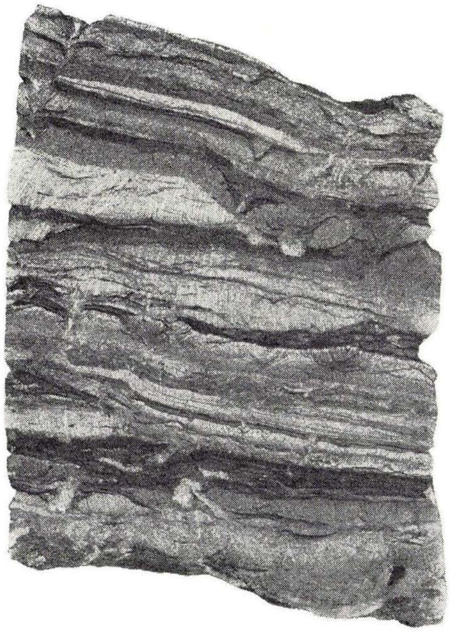


Fig. 7. Rødby 1; face cut in the core 2257′–2270′; Rhaetic; alternating layers of light calcite-cemented siltstone and dark claystone locally with slight deformation; with cone-in-cone structure. $\times ^2/_3$.

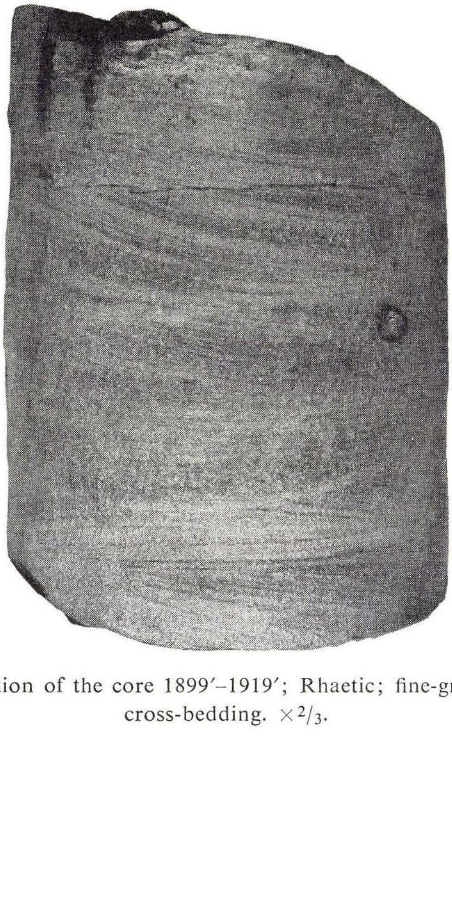


Fig. 8. Rødby 1; section of the core 1899′–1919′; Rhaetic; fine-grained sandstone with cross-bedding. $\times ^2/_3$.

Fig. 9. Horsens 1; section of the core 1449–1455 m; Lias; shell-bearing marine claystone with thin silt layers, laminated, with deformed bedding presumably caused by burrowing organisms (see BOUMA, 1965). ×2/3.

Fig. 10. Horsens 1; section of the core 1583–1587 m; Rhaetic; above, sandstone with weak cross-bedding, below, alternating thin bands and lenses of siltstone and claystone, partly deformed as a result of the work of burrowing organisms. ×2/3.

these two sections with almost identical development are connected geographically, and they have been assigned to a lithostratigraphical formation, termed the *Ullerslev Formation* after the well Ullerslev 1. Apart from the ostracod-bearing layer at the base, this formation seems to be of non-marine origin; it seems reasonable to assume that it was formed as a deltaic deposit in the border zone between the existing land area and the Rhaetic basin.

In the well Slagelse 1 a part of the section has been assigned to the Rhaetic. The interval referred to consists of predominantly clayey sediments with some content of siltstone and lignite. Ostracods have been found in some samples, which may indicate that some parts of the sequence are of marine origin. Since the section is not, however, represented by cores, a more detailed evaluation is not possible at present. Nevertheless it can be concluded, if only from the general lithology and the geographical position of the locality, that this is a development more influenced by the basin than was the sequence represented in the Ullerslev Formation. It is possible that this interval at Slagelse can be assigned to the Vinding Formation.

The presence of Rhaetic has not been demonstrated with certainty in the Lavø well. The borings that have been assembled in the Øresund diagram do not include Rhaetic beds, but it is safe to state that such beds are present at a slightly lower level, since in the adjoining part of Skåne there is a Rhaetic sequence consisting of coal-bearing, non-marine deposits (Troedsson, 1951). Equivalent sediments are known from the Höllviken well (Brotzen, 1950). It should be added that in Bornholm as well as in Fyledalen in Skåne the Rhaetic is evidently not present (Gry, 1960; Magnusson, Lundqvist and Regnéll, 1963, p. 319).

LIAS AND TRANSITION TO DOGGER

The Lias, as it occurs in the Øresund area, is represented by sedimentary strata of rather complicated constitution, including both marine and non-marine deposits. As a result, the sequence has been subdivided into several formations, which will be discussed in the following section.

The *Hälsingborg Formation* belongs in age to the oldest part of the Lias, to be precise, alpha-1 and alpha-2 (Troedsson, 1951). It consists of beds of dark clay and light sand, often in alternation, with subordinate coal occurrences; seat-earth beds are often associated with the coal seams. Cross-bedding and slump structures are of frequent occurrence. Marine fossils occur sparsely in certain horizons. At some places in the formation, where layers of clay and sand-silt alternate, the clay can be seen to contain abundant, almost vertical cracks, which are filled with fine sand and silt and strongly folded; identical sedimentary structures are mentioned by v. Engelhardt (1957). Bölau (1951), has described similar structures from the Rhaetic in north west Skåne; these are on a larger scale and are considered by him to be fossil earthquake cracks. The

Hälsingborg Formation is known to occur in a substantial part of north-west Skåne, where it is about 200 m thick. It is considered to be a predominantly non-marine border facies, presumably of estuarine origin. The *Döshult Formation*, which overlies the Hälsingborg Formation, has been referred to the Lias alpha-3 (TROEDSSON, 1951). It consists of a ca. 70 m thick, to a large extent rather coarse-grained sandstone unit, whose upper part contains a rather rich marine fauna, which includes molluscs. This formation is also known to occur in north-west Skåne. It has clearly been formed under marine conditions, presumably in a rather shallow-water coastal area. The succeeding *Pankarp Formation* has, on the basis of its microfossil content, been assigned to Lias beta and the transition zone between Lias alpha and Lias beta. It is more than 100 m thick and consists of claystone coloured grey-black, greenish grey and reddish brown. Streaks of light siltstone are present in the claystone. Except for a few subordinate, partly coal-bearing bands, the formation seems to be of marine origin. It is also known to occur in Skåne (BÖLAU, 1954, 1959). The Pankarp Formation is overlain by the *Kattslösa Formation*, a sedimentary sequence more than 100 m thick, consisting of sand and clay beds, locally very rich in shells; sand is obviously the predominant component. The bedding is strongly disturbed in many places by tunnels made by organisms. This is clearly a marine deposit. The fossil content shows that the formation can be referred to the Lias gamma and the transition zone between beta and gamma. It is known from the adjacent area of Skåne (TROEDSSON, 1951). The next beds in Øresund belong to Lias delta, but the boundary with Lias gamma is not present in the boreholes. The Lias delta deposits consist of rather shell-rich silt beds with a greyish colour; numerous tracks of burrowing organisms obscure the bedding in much of the sequence. Its marine origin is clear. Beds of completely comparable development are evidently not known in Skåne, where there is instead the so-called "upper multicoloured series" (BÖLAU, 1959), which belongs to Lias delta and epsilon. In Øresund this sequence is possibly represented by the youngest Lias beds, which consist of greenish clay with streaks and bands of sand; this deposit seems to be of non-marine origin.

The Lias beds described in outline from the Øresund borings are, because of their frequent changes of facies, rather different from the equivalent beds in the other borings in the Danish Embayment. In these last-named borings a clay sequence is met with almost everywhere. The clay contains varying amounts of silt; its colour is greyish, ranging from rather light to very dark, almost black, often with brown and green tints. In places there are intercalations of siltstone and fine-grained sandstone in the form of streaks, lenses and thin bands. Clay-ironstone concretions are rather common. The beds contain molluscs and microfossils (foraminifera), which prove conclusively that it is of marine origin. Plant remains are also found here and there. In the claystone there are in places tracks of organisms in the form of light-coloured, more or less horizontally running passages, which seem to correspond to the Chondrites

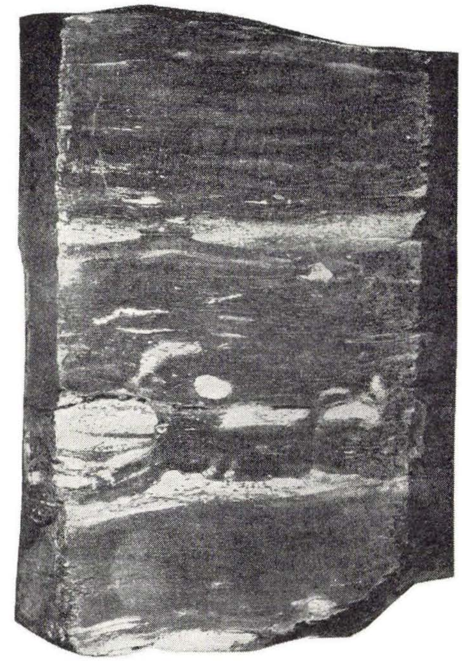


Fig. 11. Rødby 1; face cut in the core 1675′–1690′; Lias; laminated relatively silt-free dark claystone with thin bands and lenses of light siltstone; the deformation is presumably attributable in part to slumping. ×2/3.

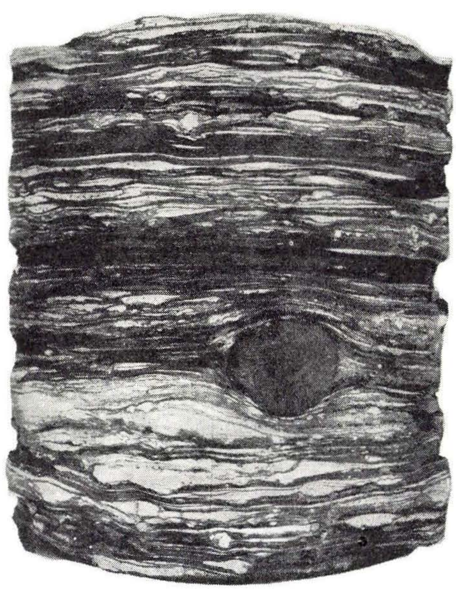


Fig. 12. Lavø 1; section of the core 2163–2166 m; Lias; alternating thin bands and lenses of dark claystone and light sandstone; with deformation around pyrite concretion. ×2/3.

tracks described by GOLDRING (1964), FARROW (1966) and others; examples of these are to be found in the English Lias. The Lias varies very much in thickness, from ca. 100 m at the margin of the basin (Skagen, Rødby) to about 700 m in the deepest part of the basin (Fjerritslev); even out in the basin, however, the thickness is subject to large variations, as shown clearly by the wells Fjerritslev 1 and 2. Apart from these differences in thickness, the development of the strata seems so uniform, not only within individual wells but also from well to well, that it was considered reasonable to assign them to one lithostratigraphical formation; this has been named the *Fjerritslev Formation* after the well Fjerritslev 2. This borehole lies well out in the basin and has a considerable thickness of Lias beds; it can thus be concluded that the most complete development is probably found here. The Fjerritslev Formation is thus the marine clay unit that succeeds the predominantly non-marine Rhaetic; chronostratigraphically it consists of the Lias, but in addition, in some areas, it includes the basal parts of the Dogger where these are developed in a marine clay facies like the Lias deposits (this will be dealt with in the next section).

In some of the borings a chronostratigraphical subdivision of the Lias has been made on the basis of microfossil content (NØRVANG, 1957). In Gassum, Lias alpha, beta, gamma and delta have been found. In Haldager, where the Lias was not drilled through, gamma and delta have been shown to occur. The lowest part of the Lias in Skagen has been assigned to alpha-3. In Rødby the presence of alpha and gamma was demonstrated, and in Vinding, alpha and beta. These results can indicate that in the deep part of the basin almost the whole of the Lias is represented by what appears to be a continuous sedimentary sequence, while it is not yet clear whether this also applies to the parts of the depositional area closer to the border of the basin.

It was stated above that the strata are marked by considerable uniformity; in spite of this, however, it is possible to trace some very slight differences. If detailed studies are made in the future, these differences may lead to a lithostratigraphical subdivision of the Fjerritslev Formation. One of these features is that in several of the wells, streaks and thin beds of siltstone and fine sandstone are more frequent in the lower part of the succession than a little higher up; in Gassum 1 such bands and streaks are present in Lias alpha, but evidently not in beta. Another point that will be mentioned here is the deflection on the Schlumberger curves at about the middle of the Lias in Frederikshavn City 1; this deflection shows that the sediment here is slightly coarser-grained than the sediments immediately above and below, a fact that is also discernible in the samples. A comparable deflection is also found in Flyvbjerg 1, Børglum 1 and Haldager 1, and it can thus be accepted that there is a continuous horizon of slightly coarser material (see fig. 13). In Haldager 1 this probably belongs to Lias gamma. In the Gassum well also, the Lias gamma is obviously a little coarser-grained than the beds above and below which have been assigned to Lias delta and beta respectively. These data give some indication that, in the

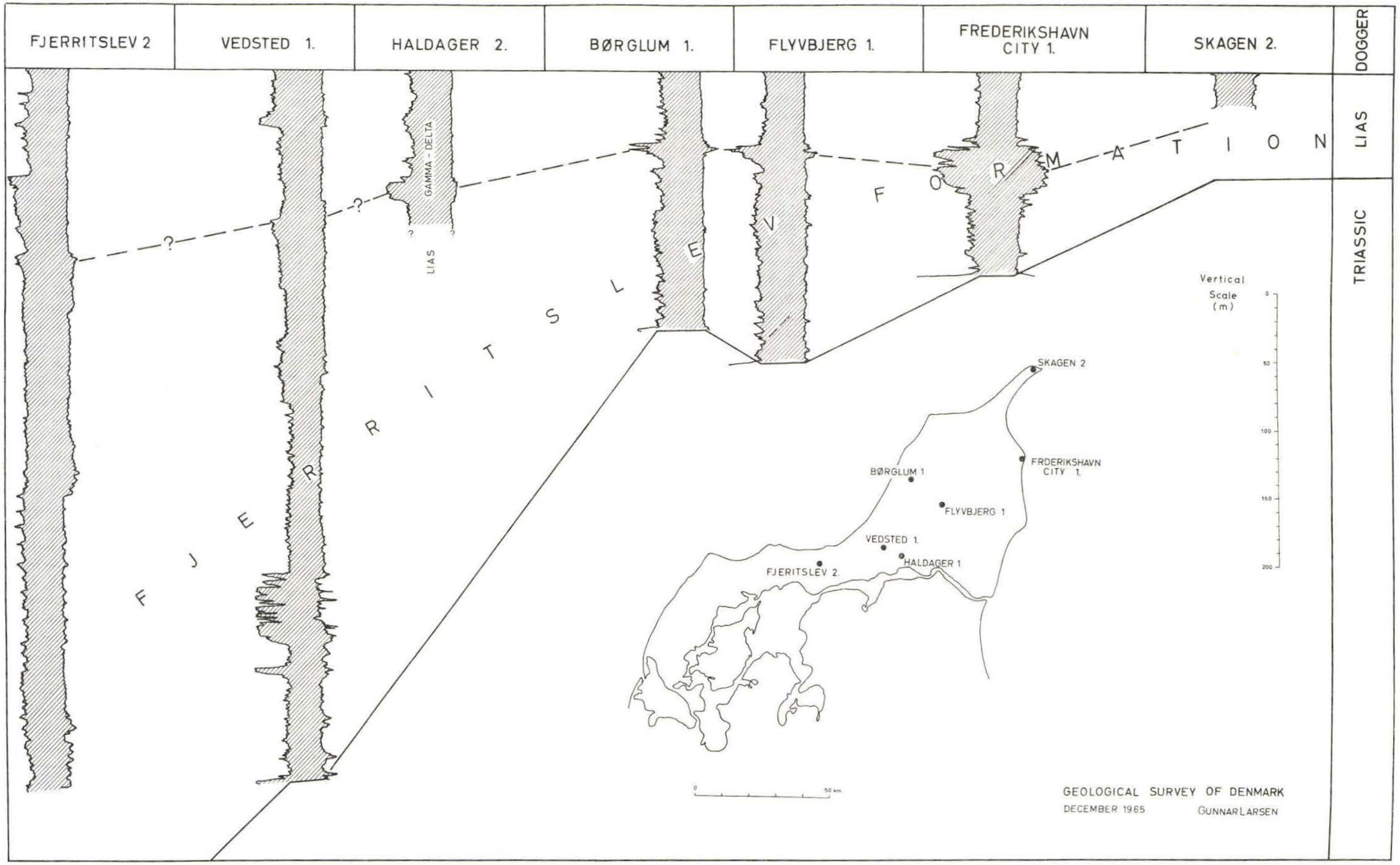


Fig. 13. The Lias sequence in the borings in north Jylland as it appears on the Schlumberger SP and resistivity curves; in this representation the boundary between the Lias and the Dogger has been made horizontal.

otherwise rather uniform Lias in north Jylland, a tendency towards a rhythmic development can be traced. It should be recalled that an apparently comparable rhythm, but much more strongly developed, is found in the Øresund section described earlier. Here coarse Döshult deposits are overlain by the fine-grained sediments of the Pankarp Formation, which is in turn overlain by the sand-dominated Kattslösa Formation; the succeeding deposits seem once more to be fine-grained.

A feature that is quite different from the other characteristics of the Fjerritslev Formation is found at the top of the Rødby section. A red-yellow-green variegated, clayey, fine sand bed about 1 m thick is found here. This variegated bed is considered to be a weathered horizon, presumably of post-Lias origin. This conclusion is based on the fact that the Lias beds are overlain directly by the Albian, so that there is here a lacuna representing the Middle and Upper Jurassic, as well as most of the Lower Cretaceous.

Finally it should be mentioned that in Bornholm a Jurassic succession over 700 m thick is known, much of which, at any rate, can be assigned to the Lias. It is subdivided into an upper and a lower coal-bearing set of beds, consisting of sand, clay and coal often in rhythmic alternation, with several horizons containing foraminifera. A marine deposit assigned to Lias gamma separates the two coal-bearing sections (GRY, 1960).

DOGGER

Middle Jurassic deposits are known to occur in the majority of the wells in Jylland, as well as in the Øresund borings; deposits of this age are not, on the other hand, present in the borings in Sjælland, Fyn and Lolland. The Dogger is, however, absent in one of the wells in Jylland, Gassum 1.

In the description of the Fjerritslev Formation in the previous section, it was stated that so far as age is concerned, this formation consists not only of Lias, but in some places in the basin also includes parts of the Dogger. This applies where the Dogger deposits, developed as a marine clay facies like the Liassic facies, follow the Lias beds without any sign of a break or alteration in the sedimentation. The wells at Vedsted and Fjerritslev provide examples of this.

In addition to this marine clay facies, there is also another main facies found in the Dogger, a sandy facies. This is present as a sequence of beds generally about 100 m thick, but locally (Haldager 1) up to 300 m, resting on the Fjerritslev Formation and extending over the major part of north Jylland, from Skagen probably as far as Horsens; as stated earlier, however, Gassum is not included in the area of Dogger development. In the well Uglev 1 the Mesozoic succession commences with a sand deposit whose chronostratigraphical position has not yet been finally settled, but up till now it has been assumed that it belongs to the Dogger (SORGENFREI and BUCH, 1964). If this assumption is valid, the

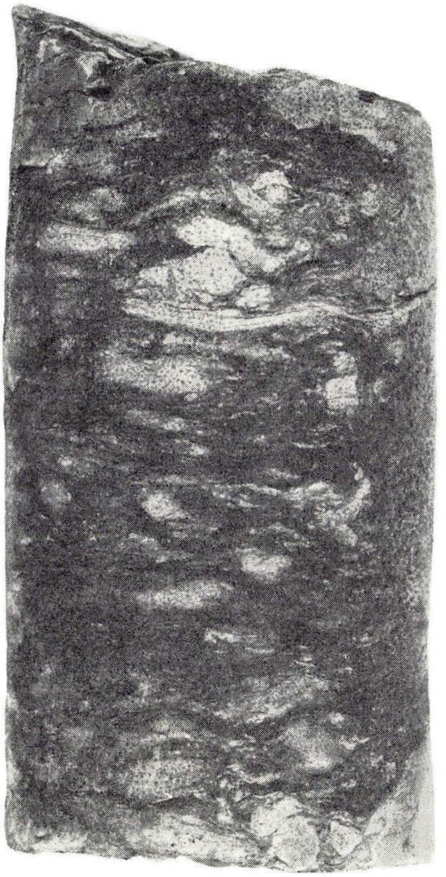


Fig. 14. Vedsted 1; section of the core 1145–1151 m; Dogger; dark silty claystone with layers and knots of light siltstone showing clear signs of slumping. $\times 2/3$.

Uglev occurrence should presumably be correlated with the above-named sand deposits. It is to be noted that so far as the lithological development is concerned this deposit seems to fit very well here.

As mentioned, the main characteristic of the lithology of this sedimentary unit in the Dogger is that it is sandy. The sand is usually rather light grey to almost whitish. In grain size it varies strongly from fine to coarse; material of gravel size appears locally. Furthermore, there occur layers of more or less silt-bearing, sometimes rather mica-rich clay with a light grey to dark grey colour. In parts of the succession the distribution of sand and clay reflect a cyclical development. Amongst the subordinate components there occurs carbonaceous material, in some cases as flakes and lenses, and in a few cases as thin seams. In association with the coal occurrences there are sometimes seat-earth beds, which show that at least a part of the carbonaceous material is autochthonous. Deposits with these characteristics must be regarded as non-marine. In addition there are beds that are clearly of marine origin as shown by their content of marine fossils and, locally, glauconite. These marine intercalations seem especially to make their appearance in the upper part of the succession. However, taking the deposit as a whole, this must be regarded as a general impression only, as some of the wells are only represented by sparse core material. If the lithological character of this sedimentary unit is considered together with its extensive development it is logical to conclude that it is a deltaic deposit that spread out into the basin from a source in the north. It should be noted that the occurrence of marine intercalations in no way conflicts with this conclusion, since the deltaic environment is a very complex environment where many different facies, both marine and non-marine, interchange (see ALLEN, 1964; KUENEN, 1950, pp. 324–330). It is considered reasonable for the time being to regard this deposit as a lithological unit, a formation; this has been termed the *Haldager Formation* after the well Haldager 1, where it has its thickest development.

The Haldager Formation is overlain in the wells Vedsted and Fjerritslev by other Middle Jurassic beds, developed as marine deposits. These pass upwards into the Upper Jurassic strata without any sign of alteration in the conditions of deposition. Marine clay deposits are also found in Vinding 1, but it has not been finally proved that these are Dogger in age.

In Øresund the Dogger is also present, as mentioned, but only a small part of the sequence is represented in the borings. The oldest part is a dark grey clay and silt deposit, clearly of marine origin as shown by the content of fossils, including ammonites. The succeeding strata are predominantly non-marine, consisting of coal-bearing clay, silt and fine sand deposits. The coal sometimes occurs in seams up to 70 cm thick, in places as part of a cyclic sedimentation: fine sand, silt, clay, coal. These coal layers are probably autochthonous since there are remains of an extensively interwoven network of roots in the underlying beds. The age of the coal-bearing deposits has not been determined with certainty, but they have been assigned to the Dogger partly because a comparable sequence is known from the locality Vilhelmsfält in north-west Skåne, and this has been referred to the Middle Jurassic (BÖLAU, 1959). It is assumed that the strata in Øresund are linked geographically to those in north-west Skåne, and they are thus termed the *Vilhelmsfält Formation*. This formation may also extend farther southwards in Skåne (LARSEN et al., 1965). In Fyledalen there occurs a ca. 350 m thick, coal-bearing sand and clay sequence, which has been assigned to the Middle Jurassic (see fig. 3 in OERTLI et al., 1961; also see TRALAU, 1966).

Finally it can be mentioned that, concerning the Bornholm Jurassic, GRY (1960) suggests the possibility that part of the non-marine, upper coal-bearing sequence was formed in Middle Jurassic times.

MALM

Beds belonging to the Upper Jurassic, or Malm, are known from these wells in north Jylland: Skagen 2, Frederikshavn City 1, Flyvbjerg 1, Børglum 1, Haldager 1, Vedsted 1, Fjerritslev 1 and 2, Uglev 1 and Gassum 1. They are not found in the borings farther south, or in the boreholes in Fyn, Lolland and Sjælland; on the other hand, Upper Jurassic is present in Øresund.

The strata in Jylland comprise two main lithological types, namely a clay deposit and a sand deposit.

As stated in the previous section, the marine clay deposition continues without interruption from the Dogger across the boundary into the Malm in the borings Vedsted 1 and Fjerritslev 1 and 2. In the wells to the north, the Upper Jurassic clays rest on the sandy Haldager Formation; this is probably also true of the borehole Uglev 1, where however there is, as mentioned, some doubt about the position of the underlying sand sequence in the stratigraphical coloumn. In Gassum 1 there is presumably an erosional boundary between the Upper Jurassic clay and the underlying Fjerritslev Formation, since the Middle Jurassic is, as stated earlier, absent here. The clay deposit seems to be of marine origin throughout the area of development since it is fossil-bearing; both molluscs and microfossils are present (SORGENFREI & BUCH, 1964). The deposit varies somewhat in grain size, some of the sediments being silt-rich. The colour also varies, from dark grey to light greenish grey. Completely different colours occur in an interval (core 3903′–3914′) in Gassum 1; at this level there is frequent alternation of brownish red and greenish grey colours, a fact that can be logically interpreted as the result of weathering effects. In these clays there are locally tracks of burrowing organisms. In the northernmost part of the area of development, the clay unit is rather thin and overlain by Upper Jurassic sand. Towards the south, the clays increase in total thickness. In Vedsted 1, where there is still a sandy covering layer the thickness is ca. 100 m. Farther west, at Fjerritslev, the sand bed is absent, and the whole of the Upper Jurassic is obviously developed as a marine clay facies; the same seems to apply to Uglev 1. The formation name *Børglum Formation*, after the well Børglum 1, has been introduced for the marine clay deposit described here. In some places it consists, as already stated, of the uppermost Dogger and the whole of the Malm; in Børglum 1 and Haldager 1 it is referred to the Oxfordian, in Gassum 1 to the Oxfordian plus basal Kimmeridgian (SORGENFREI and BUCH, 1964).

The other main facies of the Upper Jurassic is, as mentioned, sandy. In its "typical" development, e.g. in the Frederikshavn City 1 section, it consists of greenish, glauconite-bearing siltstone and fine-grained sandstone, with a content of marine fossils. In places there are thin limestone bands; thin-section examination of these has shown that the lime content is present as a very coarse-grained matrix enclosing sand particles consisting of quartz, feldspar and glauconite (fig. 16), so that the material ought really to be called a calcareous-cemented fine sandstone; this calcareous cement is presumably the

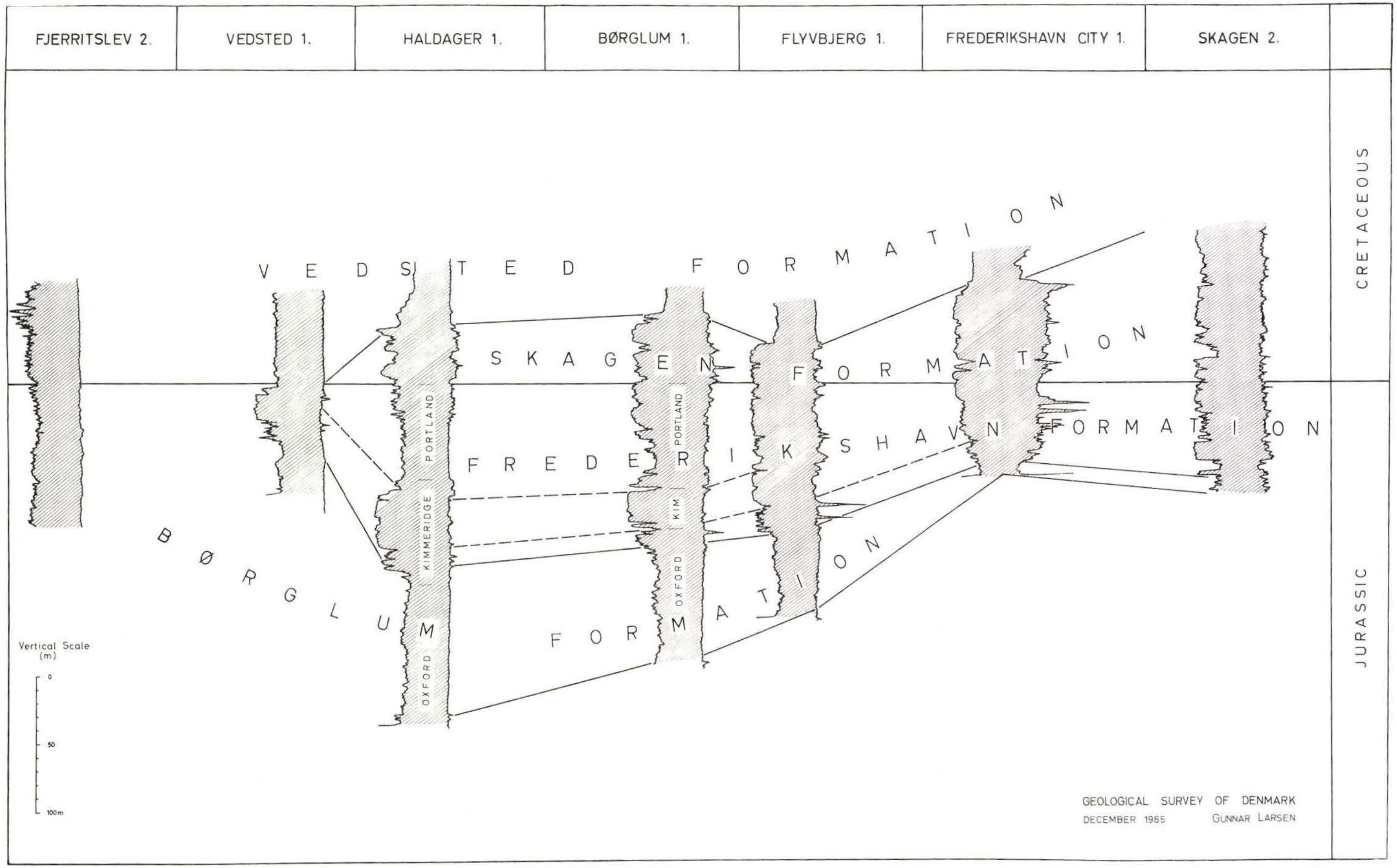


Fig. 15. The sequence spanning the Jurassic/Cretaceous boundary in the borings in north Jylland (cf. fig. 13) expressed by the Schlumberger SP and resistivity curves; in this representation the boundary between the Jurassic and the Cretaceous has been made horizontal.

result of diagenesis. As subordinate elements there are beds of claystone; here and there in these there occur clay-ironstone nodules, some of which have septarian structure. In a few places in the sand beds cross-bedding has been observed. A short interval (between samples 25 and 30, Plate VI) in Haldager 1 consists of relatively dark-coloured, rather coarse material of obviously non-marine origin. Apart from this example, it seems that the sand deposit can be considered, on the basis of its nature and distribution, as a marine border facies in the Upper Jurassic depositional area. The formation name *Frederikshavn Formation* is introduced for this unit, after the well Frederikshavn City 1. It rests, as stated, on the clayey Børglum Formation (fig. 15) throughout the area of its development. In the borings at Skagen and Frederikshavn it is limited upwards by a clearly non-marine sand deposit, which has been assigned to the Lower Cretaceous (see next section); this appears to apply to Flyvbjerg and Børglum also. In Haldager 1 the situation is less clear, in that the Lower Cretaceous sand bed seems to have both marine and non-marine features; however, the analytical results presented here (Plate VI) suggest that the upper boundary of the marine Frederikshavn Formation lies at about the place in the succession that up till now has been regarded as the Cretaceous/Jurassic boundary. The age of the Frederikshavn Formation can, in the wells Børglum 1 and Haldager 1, be given as Kimmeridgian and Portlandian (SORGENFREI and BUCH, 1964).

The Upper Jurassic is also present in Øresund, in the form of a greenish to dark grey silt and clay deposit, containing subordinate limestone beds and abundant fossils locally. This is a predominantly marine unit, whose age has been determined as Kimmeridgian. Its total thickness is still unknown, but it is known to exceed 9 m. On the suggestion of mag. scient. O. BRUUN CHRISTENSEN, the deposit has been called the *Fyledal Clay* after the locality in Skåne, Fyledalen, where there is a comparable sequence of greenish clays, over 100 m in thickness (OERTLI et al., 1961; MAGNUSSON et al., 1963, p. 319).

LOWER CRETACEOUS

As mentioned earlier the Lower Cretaceous in the borings in northern Jylland (Skagen 2, Frederikshavn City 1, Flyvbjerg 1, Børglum 1, Haldager 1) commences with a sand deposit. This has its greatest thickness at Skagen and thins out southwards. The material consists mainly of greyish, fine-grained sand containing plant remains; at Haldager there is also some content of microfossils (foraminifera). It seems reasonable to regard this sand deposit as a deltaic product that spread out into the basin from a source in the north. Here in the marginal area of the delta there has clearly been some marine influence operating; marine influence can also be traced at Frederikshavn in the form of a content of glauconite in the uppermost part of the sands. Where geographical extent is concerned, this sand deposit seems to be a well defined

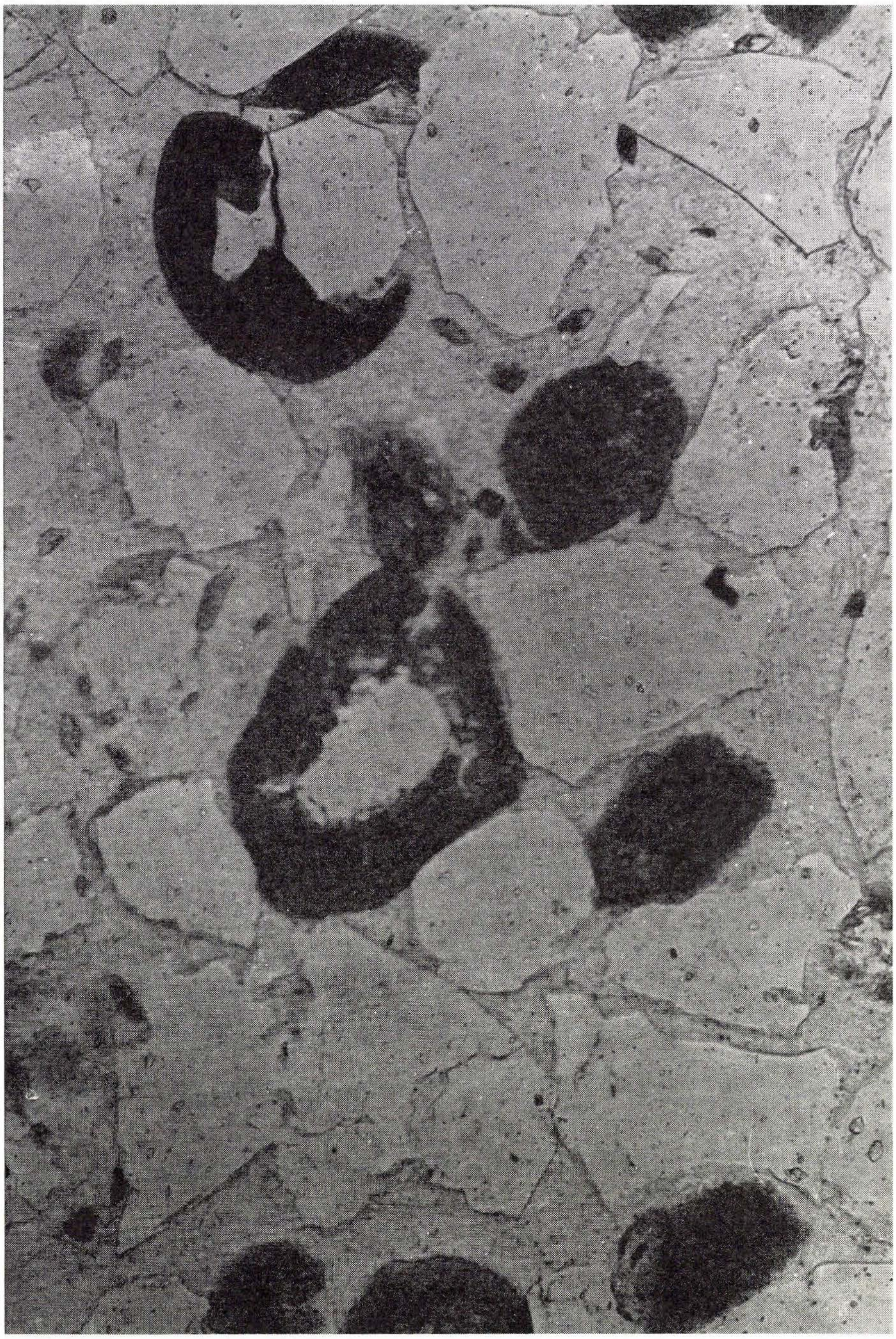


Fig. 16. Frederikshavn City 1; part of thin section (×360; ordinary light) of sample no. 10; Malm; sand grains consisting of glauconite and quartz surrounded by a calcite matrix composed of one crystal; some of the quartz grains show clear signs of authigenic overgrowth.

unit (see fig. 15). It has been called the *Skagen Formation* after the well Skagen 2. This is obviously a local Wealden facies.

At Skagen the Skagen Formation is overlain directly by the Pleistocene. In the borings situated to the south (Frederikshavn City 1, Børglum 1, Haldager 1) it forms the base for other Lower Cretaceous deposits, which consist predominantly of clay and silt of more or less dark grey colour, and have in places a considerable content of glauconite and fossils. The same clay and silt deposit also occurs in the wells Vedsted 1, Fjerritslev 1 and 2, and Gassum 1; in these wells the deposit rests directly on the marine Upper Jurassic without a sandy intervening bed. In most of the area that the wells named here represent, the deposit can reasonably be regarded as a formation. It is termed the *Vedsted Formation* after the boring Vedsted 1. Although it is true that there is only a very modest amount of core material from this well, it has been shown that the ca. 525 m thick deposit at this locality comprises the whole of the Lower Cretaceous: Valanginian, Hauterivian, Barremian, Aptian, Albian (Sorgenfrei and Buch, 1964); this presumably applies also to the well Fjerritslev 2, where the thickness is 775 m. The marine character referred to earlier appears to apply to all the borings mentioned, with the exception of Frederikshavn City 1; in this well most of the sequence is also clearly marine as shown by the locally very large content of glauconite as well as by the presence of fossils (foraminifera), but it seems that two sections (samples 175–177 and 205–210, see Plate III) must be regarded as non-marine. It is possible that these two sections represent tongues of the previously mentioned Skagen Formation, which intervene and divide the Vedsted Formation into several sections. This view may appear very reasonable, but it can not really be finally verified on the basis of the existing material, because, amongst other reasons, it is presumably only an erosional remnant of the Skagen Formation that is represented in the well Skagen 2. Regardless of how these features may be interpreted, it seems clear that the boring at Frederikshavn represents the northern boundary area of the Vedsted Formation; the fact that the content of material of sand-grain size is greater here than in the wells farther south also suggests this. As mentioned, the Vedsted Formation does not rest on the same formation throughout the whole of the area referred to. At Frederikshavn, Flyvbjerg, Børglum and Haldager the substratum is composed of the sandy Lower Cretaceous Skagen Formation; at Vedsted and Gassum it is found directly above the sandy Upper Jurassic Frederikshavn Formation and at Fjerritslev directly above the clayey Upper Jurassic Børglum Formation. At the last-named place the lower boundary is not sharply defined, but it seems however that its position can be established by the fact that the Upper Jurassic clay is less silty than the Lower Cretaceous clay. The formation is bounded upwards, in all the wells named, by the Upper Cretaceous. The basal parts of the Upper Cretaceous (Cenomanian and to some extent Turonian) do indeed contain a great deal of terrigenous material of the same type as in the Vedsted Formation, but at the same time the carbonate content is so large that these deposits are markedly different from the Vedsted Formation and can be grouped naturally with the rest of the Upper Cretaceous deposits.

Up till now the description has concerned the Vedsted Formation in the northernmost part of Jylland, but it appears to be present farther south as well. This applies for example to Uglev 1 where the various features, apart from total thickness, are reminiscent of Fjerritslev, partly because there is a sharp lithological boundary at the top with the Upper Cretaceous, and also because the lower boundary with the Upper Jurassic can hardly be recognized lithologically. A Lower Cretaceous clay deposit of predominantly dark grey colour and obviously marine origin also occurs in the wells at Vemb, Vinding, Slagelse and Ullerslev; it is considered that these occurrences belong to, and constitute a part of, the Vedsted Formation. In both the lower and upper formation boundaries these four wells are different from those in north Jylland. The formation does not rest on Upper Jurassic deposits, but at Vemb and Vinding on Middle Jurassic, at Slagelse on Lower Jurassic and at Ullerslev on Rhaetic deposits; in all four cases there is presumably a disconformity. The formation is not bounded at the top by Upper Cretaceous, but by other Lower Cretaceous deposits of an entirely different lithological type. In Vemb 1, where the Vedsted Formation is ca. 145 m thick, it is referred to Valanginian, Hauterivian and Barremian, and in Vinding 1 the Valanginian at any rate is represented (SORGENFREI and BUCH, 1964). In Ullerslev 1 the Hauterivian and Aptian are stated as being represented in the sequence, which is only ca. 6 m thick. In Slagelse 1 the ca. 9 m thick deposit has not been precisely dated, but it seems to agree very well lithologically with the occurrence at Ullerslev; for instance, both contain oolitic material.

The Lower Cretaceous strata that overlie the Vedsted Formation in the wells Vemb 1, Vinding 1, Ullerslev 1, Slagelse 1 and Gassum 1, consist of reddish to red-brown, lime-rich sediments; comparable beds are found at Horsens and Rødby, where the substratum consists of, respectively, Middle and Lower Jurassic. At the localities named here the bed thickness is in the range 5–20 m. According to the available determinations of the carbonate content, these reddish sediments must be termed marl or argillaceous limestone. The deposit is fossiliferous and its marine origin is evident. Age determination shows the age to be Albian and, in some places, Upper Aptian (SORGENFREI and BUCH, 1964). There can be no doubt that it is one and the same deposit that is encountered in the boreholes named; the term *Rødby Formation* is introduced for this deposit, after the well Rødby 1, from which well there is good core material. In the Danish Embayment the Rødby Formation is, as already mentioned, only developed in the southern part; its northern boundary runs north of the line Vemb 1, Vinding 1, Gassum 1, Slagelse 1. However in addition, the area of development of the formation extends even farther south, over the Ringkøbing-Fyn High and the northern parts of the North German

Basin (SORGENFREI and BUCH, 1964; GRIPP, 1964, p. 57). It thus appears that this formation, in both its lithogenetic and its palaeogeographical aspects, has more in common with the succeeding Upper Cretaceous beds than with the preceding Lower Cretaceous.

In the well Lavø 1 the Lias is overlain by whitish sandstone and dark grey claystone, whose age is stated to be Lower Cretaceous. Above this follows a greenish, glauconite-bearing sandstone, which has been dated as Albian. It is still not clear how these Lower Cretaceous deposits ought to be placed in relation to the depositional units described previously; for the time being they are grouped under the name *Lavø Formation.*

Lower Cretaceous is not present in the Øresund borings. In Skåne the Lower Cretaceous is known in Wealden facies from the Höllviken boring (BROTZEN, 1950). Wealden beds are also found in Bornholm, where GRY (1956, 1960) has established three formations: the Rabekke Formation, the Robbedale Formation and the Jydegaard Formation. These represent in age the boundary zone Cretaceous/Jurassic (CHRISTENSEN, 1963, 1964, 1966). These Wealden deposits in Skåne and Bornholm are possibly equivalent to the Skagen Formation in north Jylland.

In the preceding account of the lithology and stratigraphy of the succession, it has been the intention to bring out the major features of the development of the facies in the basin during Rhaetic, Jurassic and Lower Cretaceous times. The establishment of the lithostratigraphical formations has been an aid in this respect. These formations are consequently rather large units which it will presumably be found appropriate to subdivide into smaller lithostratigraphical units in future detailed studies. An outline of the occurrence of the formations in the borings is given in Table I. The formations are also shown in the profile diagrams (Plates II–XVII).

MINERAL CONTENT

The main subject of this investigation is, as mentioned, the mineral distribution in the grain size fraction 75–250 μ; the results are given in the profile diagrams, plates II–XVII. These results will be discussed in the following part of the account and it will be attempted to discover the reasons for the mineral distribution; before this is done, however, some comments will be made on the individual minerals and mineral groups.

COMMENTS ON THE MINERALS

In the following review the minerals are mentioned mainly in the order in which they are recorded in the diagrams, i.e. the light minerals are treated first. The mica minerals, which are found in both the light and the heavy fractions, are placed between these two groups.

Table I Outline of the occurrence of the lithostratigraphical formations in the 15 deep borings.

All depths are in m below the surface. (?) indicates that it is uncertain if the interval really belongs to the formation mentioned. (+) indicates that the formation has not been drilled through.

		Skagen No. 2	Frederikshavn City No. 1	Flyvbjerg No. 1	Børglum No. 1	Haldager No. 1
Lower Cretaceous	Lavø Formation	–	–	–	–	–
	Rødby Formation	–	–	–	–	–
	Vedsted Formation	–	358–506	520– 750	507– 750	417– 782
	Skagen Formation	214–326	506–579	750– 777	750– 804	782– 825
Jurassic	Frederikshavn Formation	326–400	579–635	777– 885	804– 930	825– 971
	Børglum Formation	400–406	635–646	885– 950	930–1009	971–1078
	Haldager Formation	406–473	646–756	950–1060	1009–1128	1078–1403
	Fjerritslev Formation	473–553	756–903	1060–1306	1128–1368	1403–1521 (+)
Rhaetic	Gassum Formation	553–564	903–980	1306–1480	1368–1524(+)	
	Ullerslev Formation	–	–	–		
	Vinding Formation	–	–	–		

		Vedsted No. 1	Fjerritslev No. 1	Fjerritslev No. 2	Uglev No. 1	Vinding No. 1
Lower Cretaceous	Lavø Formation	–	–	–	–	–
	Rødby Formation	–	–	–	–	1292–ca. 1300
	Vedsted Formation	457– 975	287–404	299–1074	538–818	ca. 1300–1367
	Skagen Formation	–	–	–	–	–
Jurassic	Frederikshavn Formation	975–1018	–	–	–	–
	Børglum Formation	1018–1120	404–543	1074–1260	818–881	–
	Haldager Formation	1120–1220	543–588	1260–1320	(?) 881–943	–
	Fjerritslev Formation	1220–1899	588–915(+)	1320–2300	–	1367–1580
Rhaetic	Gassum Formation	1899–2065(+)		(?) 2300–2326	–	–
	Ullerslev Formation			–	–	–
	Vinding Formation			–	–	1580–1720

		Gassum No. 1	Horsens No. 1	Ullerslev No. 1	Rødby No. 1	Lavø No. 1
Lower Cretaceous	Lavø Formation	–	–	–	–	1940–2069
	Rødby Formation	997–1002	1165–1170	801–820	459–469	–
	Vedsted Formation	1002–1085	–	820–826	–	–
	Skagen Formation	–	–	–	–	–
Jurassic	Frederikshavn Formation	1085–1186	–	–	–	–
	Børglum Formation	1186–1198	1170–1220	–	–	–
	Haldager Formation	–	1220–1294	–	–	–
	Fjerritslev Formation	1198–1513	1294–1569	–	469–557	(?) 2069–2290
Rhaetic	Gassum Formation	1513–1642	1569–1597	–	–	?
	Ullerslev Formation	–	–	826–978	557–713	
	Vinding Formation	(?) 1642–1710	(?) 1597–1642	–	–	

Glauconite is found locally in very large amounts in the light fraction. Glauconite normally occurs as rounded, aggregate-polarized grains of light to dark green colour, occasionally with yellowish and brownish tints; larger dark green grains can be completely opaque in the centre. In a few grains a central, clastic sand grain can be found. Some are full of shrinkage cracks.

Several distinctive types of glauconite grain are present in the upper glauconite-bearing horizon (samples 146–161) in Frederikshavn City 1; fig. 17 shows some examples of these grains. Some can be seen to be developed as casts of foraminifera, while others contain inclusions of remains of organisms – these evidently represent radiolaria. Only a small minority of the last-named show the radiolarian skeleton clearly depicted in detail; the majority of the grains contain only rather small solution remnants of the skeleton. The surface of the radiolaria-bearing grains often seems to be characterized by wear and sometimes by fracture surfaces. This was observed most clearly in a rather large, compound grain consisting of "normal, structureless" glauconite containing a complete and also a half glauconite grain, both with remains of organisms. This feature may indicate that at least some of these grains are the result of secondary deposition on earlier-formed material. Comparable radiolaria-bearing grains have only been observed in a very few cases in other parts of the sequence; the samples 87–106 in Haldager 1, for instance, contain a very small number of these grains. Yet another type of glauconite is present in the upper glauconite-bearing horizon in Frederikshavn City 1; examples of this are shown in fig. 17, f and g. As can be seen, these are grains with fibrous structure; the fibres have a positive elongation and are pleochroic (α' greenish, γ' yellowish). Judging by the grain structure (fig. 17), it seems more than likely that this type of glauconite has originated by replacement of calcareous shells. The surface of these grains seems also to be characterized by wear.

Chemical analyses of four rather pure glauconite samples from Frederikshavn City 1 have been made by civilingeniør Birthe Dinesen, and the results of these are given in Table II; the content of glauconite as determined by petrographical analysis is also given here. The first three samples, which represent the upper glauconite horizon, have, when the glauconite percentage is taken into account, rather similar chemical composition. The fourth sample, which comes from a horizon a little lower down in the section, is different from the others, one of the differences being that the SiO_2 content is rather high. If these results are compared with the chemical analyses of glauconite published by Hadding (1932), they all seem to be rather rich in SiO_2 and relatively poor in K_2O.

In certain samples, most clearly in sample no. 175 from Frederikshavn City 1, there are indications that the glauconite has been wholly or partly broken down as a result of weathering effects. Sample no. 175 is limonite-coloured, which is in itself a sign that it represents a weathering horizon. It was mentioned earlier that during the acid treatment not only the carbonate content but also the limonite content was removed. During the petrographical investigation only a few unaltered glauconite grains were found, but in some grains, evidently consisting of amorphous silica (a colourless, isotropic substance with very low refractive index, full of shrinkage cracks – see fig. 18), there occur diffuse remnants of greenish glauconite. It is considered that this is the result of weathering effects, by means of which the glauconite has been broken down into other substances, including limonite and opal. Comparable phenomena have been reported by Gry (1935, p.101) from the Danish Paleocene. Opal-like grains answering to this description are found in several samples from the Dogger in Frederikshavn City 1 as well as in Skagen 2 in the samples no. 35–67 (Malm). It is to be noted that during the counting the opal grains containing distinct glauconite remnants were recorded under the heading "glauconite", whereas opal without visible glauconite content was included in the group "diverse aggregates" – see below.

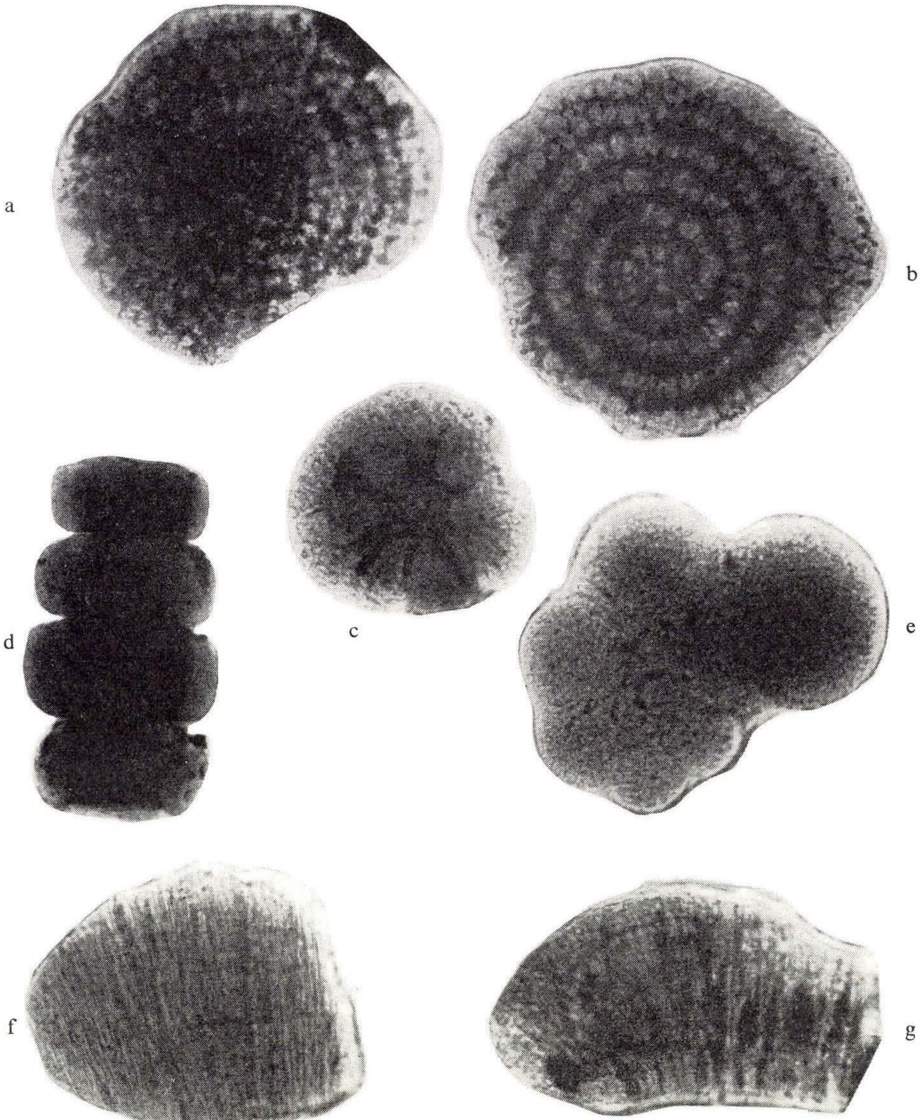


Fig. 17. Examples of glauconite grains with structure inherited from former organisms; Frederikshavn City no. 1. a, b and c contain inclusions of parts of radiolarian skeletons; d and e are casts of foraminifera; f and g are fibrous glauconite grains presumably formed by replacement of shell fragments by glauconite.

a: sample no. 159; b: sample no. 160; c: sample no. 156; d: sample no. 156; e: sample no. 148; f: sample no. 148; g: sample no. 148. ×270.

Table II Chemical analyses of glauconite samples from Frederikshavn City 1.

Sample no.	151	160	161	224
SiO_2	58.9	55.1	55.7	62.7
Al_2O_3	} 9.6[1]	} 9.7[1]	} 9.5[1]	10.5
TiO_2				0.3
Fe_2O_3	16.2	19.4	19.5	13.2
MnO	0	0	0	0
CaO	0.7	0.4	0.6	0.6
MgO	1.4	1.3	1.2	0.6
K_2O	5.4	5.5	5.3	4.9
Na_2O	0.3	0.2	0.2	0.2
P_2O_5	$<$ 0.1	$<$ 0.1	$<$ 0.1	$<$ 0.1
loss on ignition	6.8	8.0	7.5	6.9
Total	99.3	99.6	99.5	99.9
Glauconite content (%) determined by petrographical analysis	93	99	96	97

[1]) TiO_2 amounts to $< 1\%$.

Fossil remains, two examples of which are shown in fig. 19, consist essentially of various types of foraminifera, of which the agglutinating are by far the most frequent. In some of the grains belonging to this group, the nature of the fossil is quite apparent (fig. 19b). Others consist of elongated to almost circular aggregates of silt or flint-like material, in which structure inherited from former organisms may be traced in the distribution of a pigment consisting of pyrite or of a brownish, isotropic, presumably organic substance. Sometimes these depictions are rather faint, and in a good many cases there are aggregates of the type mentioned, which lack visible structure from former organisms. It is possible that the last-named are also remnants of organisms, but since concrete evidence is lacking, these were recorded as "diverse aggregates" – see below.

Plant remains include angular fragments and flakes of coal as well as fragments with distinct plant structure (fig. 20); a very few consist of spores.

Diverse aggregates is the term for a heterogeneous group of components. As already stated, this includes opal grains, which presumably represent the remains of weathered glauconite, as well as aggregates that may perhaps be unrecognizable remnants of agglutinating foraminifera. These two groups are, however, not particularly prominent in amount. Of greater quantitative significance are the fragments of siltstone and fine sandstone as well as, particularly, the so-called "brown aggregates".

These last-named are especially common in clayey sediments. They are more or less elongated, as a rule rounded aggregates built up of a very fine-grained, brownish substance, which in some cases seems to be isotropic, in other cases clearly anisotropic; the refractive index is above that of Canada balsam. In the brown aggregates inclusions of quartz of silt size, small particles of pyrite, fragments of plant material and sometimes pellets of green glauconite can be found. Fig. 21 shows a few examples of these brown aggregates. On the basis of information available it can be concluded that the groundmass in these aggregates

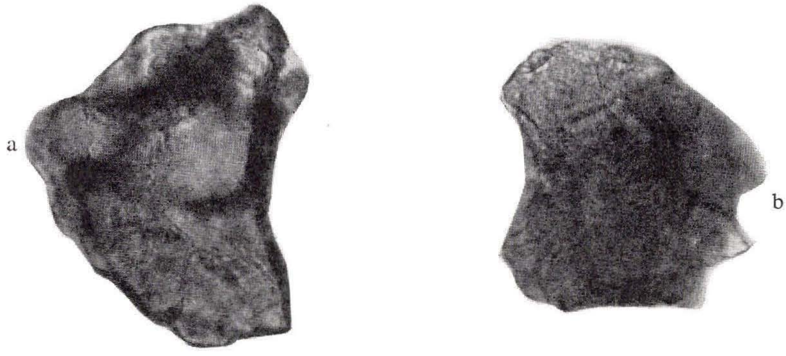


Fig. 18. Examples of opal grains presumably formed by weathering of glauconite grains; Frederikshavn City 1; sample no. 175. ×270.

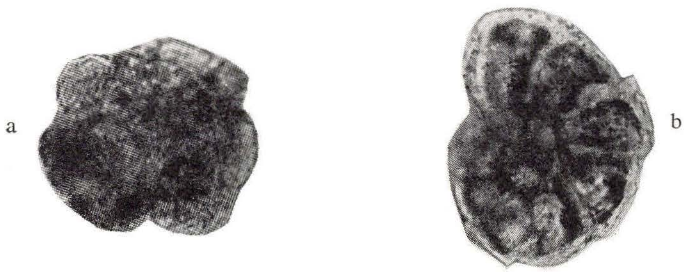


Fig. 19. Examples of grains consisting of fossil remains; Frederikshavn City 1; a: sample no. 146; b: sample no. 167. ×270.

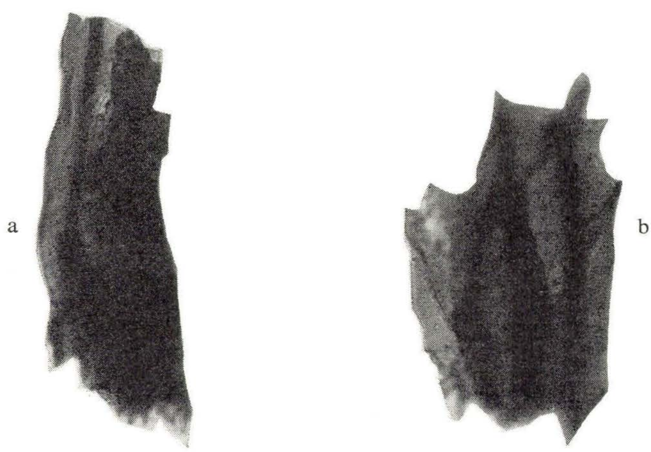


Fig. 20. Examples of plant fragments; Frederikshavn City 1; sample no. 213. ×270.

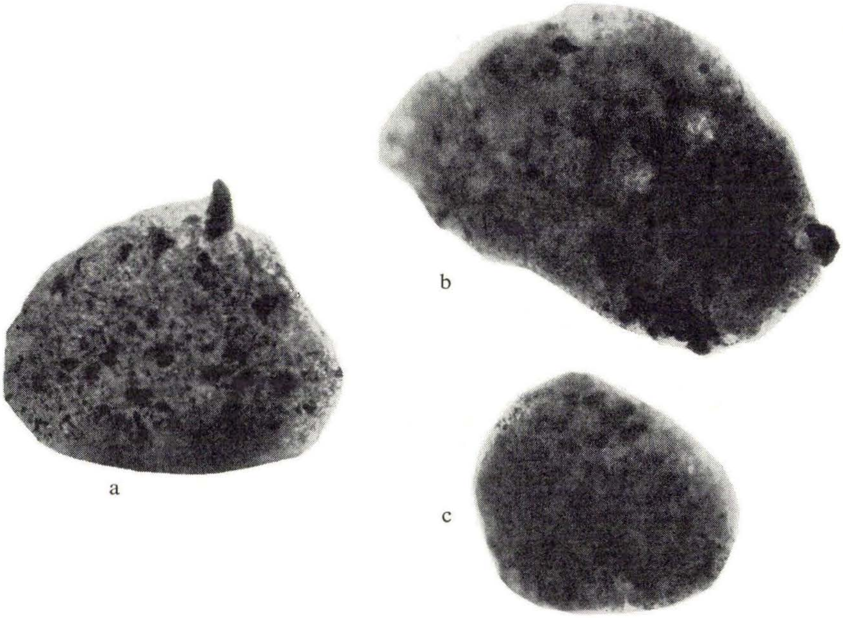


Fig. 21. Examples of "brown aggregates" (pellets); a: sample no. 51, Frederikshavn City 1; b and c: sample no. 8, Uglev 1. ×270.

consists of clay material, and that the aggregates can be presumably assigned to the category "clay pellets". In order to find out more about the composition of these aggregates, civilingeniør BIRTHE DINESEN has made chemical analyses of a number of samples of the light fraction. Table III shows the results from the samples in which the aggregates are present in large amounts (see the petrographical data given at the bottom of Table III). It can be seen that there is some variation in composition from sample to sample, a feature that is evidently not connected with the amount of brown aggregates in the samples, but is possibly related to the content of impurities such as quartz in the aggregates. If a comparison is made with Table II it can be seen that these aggregates have a substantially lower content of Fe_2O_3 and K_2O than the glauconite. Comparing with various analyses of clay material (GRIM, 1953, pp. 370–372; GRAFF-PETERSEN, 1961, p. 98), there is such good agreement that it can be regarded as being confirmed that these particular aggregates consist of clay material containing varying amounts of other minerals such as quartz and feldspar, as well as organic material. The amount of organic material was determined by loss on ignition after first removing the inorganic components by decomposition with HF and H_2SO_4 and subsequent washing of the residue with HCl and H_2O. The results obtained were as follows:

Sample no.	57	74	133	134	139	144	20	28	8	11
Org. mat. (in %)	–	–	1.3	1.3	1.1	1.7	2.0	11.7	4.9	–

It should be noted that the difference between the loss on ignition given in Table III and the data shown here is equal to the inorganic loss on ignition, which, it is presumed, mainly represents OH groups associated with the clay material, and H_2O; in this connection it is appropriate to refer to fig. 22, which shows that this loss on ignition is proportionate to the

Table III Chemical analyses of »brown aggregates« (pellets)

Boring	Frederikshavn City 1		Haldager 1						Uglev 1	
Sample no.	57	74	133	134	139	144	20	28	8	11
SiO_2	50.2	62.5	67.3	67.8	72.2	66.8	61.9	48.4	55.3	57.4
Al_2O_3	} 29.9[1])	20.6	15.5	14.7	13.4	15.6	17.5	21.4	19.5	21.2
TiO_2		0.6	0.6	0.6	0.5	0.6	1.0	0.8	1.4	0.6
Fe_2O_3	4.6	2.6	4.8	4.6	3.2	4.4	5.1	4.9	6.3	5.1
MnO	0	0	0	0	0	0	0	0	0	0
CaO	0.7	0.4	1.1	1.2	1.1	1.2	0.7	0.8	0.14	0.9
MgO	0.1	0.5	1.0	1.5	1.9	2.1	0.7	0.6	1.0	0.7
K_2O	2.1	2.0	2.7	2.8	2.4	2.7	3.7	2.1	3.5	3.5
Na_2O	0.2	0.2	0.3	0.3	0.4	0.3	0.4	0.2	0.4	0.4
P_2O_5	< 0.1	0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.06	0.13
loss on ignition	12.4	10.4	6.5	6.3	5.6	6.8	8.1	20.7	11.8	10.4
Total	100.2	99.9	99.8	99.8	100.7	100.5	99.1	99.9	99.4	100.3
Amount (%) of brown aggregates determined by petrographical analysis	98	82	95	96	97	95	99	100	100	98

[1]) TiO_2 amounts to $<1\%$.

Al_2O_3 content. When the grains are heated they turn pale without any incandescence phenomena or formation of soot, which may indicate that the organic material is present as volatile, non-inflammable compounds. As mentioned, these aggregates can presumably be regarded as "clay pellets". On the basis of the existing data it is not possible to come to any final conclusion, but it seems logical to assume that at any rate some of the aggregates represent excrement from organisms; they are thus presumably a type of microcoprolite. It must be stated in addition that there is nothing in the present analytical data to suggest that the aggregates are chamosite-bearing (cf. PORRENGA, 1965).

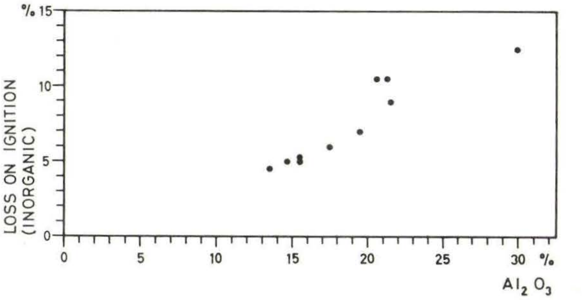


Fig. 22. The relation between the content of Al_2O_3 and the inorganic loss on ignition found by chemical analyses of "brown aggregates" (pellets, see Table III and text).

There is still another comment to be made about the chemical analyses in Table III. It is apparent from these data that the ratio Al_2O_3/Na_2O is high, varying between 33.5 and ca. 150. According to PETTIJOHN (1957, p. 509), the Al_2O_3/Na_2O ratio can be taken as an expression of the maturity of fine-grained sediments in the same way as the quartz/feldspar ratio in the case of coarser-grained sediments. The rather high values given here should indicate that these fine-grained materials are mature, i.e. strongly affected by weathering.

Quartz is one of the main minerals in the sediments. The quartz is undoubtedly mainly clastic, but in a number of cases unmistakeable signs of authigenic growth have been detected. This appears most clearly in the thin section of the Upper Jurassic "limestone" in Frederikshavn City 1 (fig. 16). In many places in the section angular quartz grains that have grown together can be seen. This growth must have taken place after the deposition, i.e. during diagenesis. Comparable phenomena are more difficult to detect in the sand preparations that the study has been mainly concerned with; a few examples can, however, be mentioned. Fig. 23 shows two well rounded quartz grains with quartz overgrowths. In one of these (a), the surface of the overgrowth is characterized by distinct rounding, which must mean that the authigenic growth in this case has taken place during an earlier phase of sedimentation. In the second grain (b), the outer surface can be seen to be angular, from which it is deduced, when the large size of the grain is also taken into account, that the quartz overgrowth was formed after deposition. The quartz stems presumably from both sedimentary and non-sedimentary source material. All well rounded grains must undoubtedly be assigned to the first-named category.

Feldspar is the term used in the diagrams to describe several different minerals. Amongst these, feldspar grains with refractive indices lower than the index of Canada balsam are by far the most frequent. To this group belong the potash feldspars, namely orthoclase and microcline, and also the acid plagioclases; the potash feldspars seem to be predominant

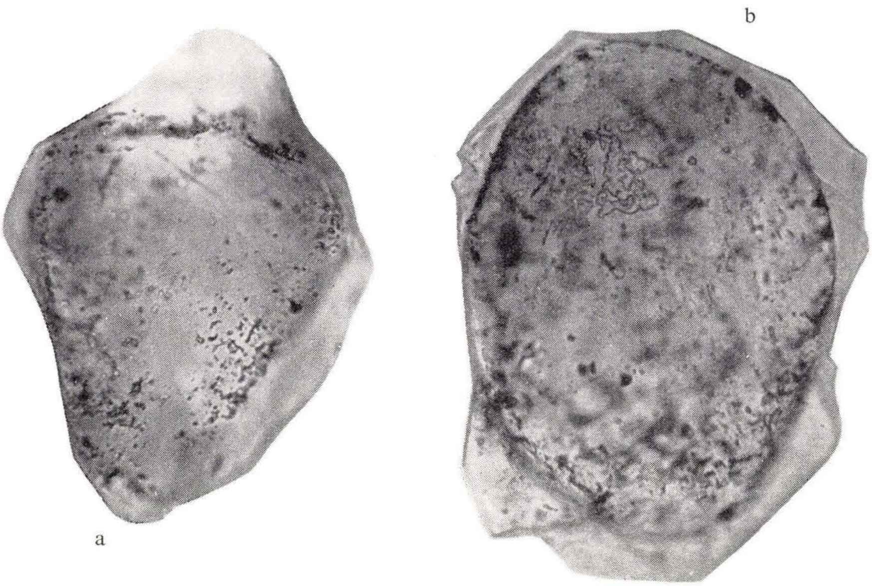


Fig. 23. Quartz grains with authigenic overgrowth; Frederikshavn City 1; a with subangular outline and b with angular outline. a: sample no. 258; b: sample no. 267. ×270.

Fig. 24: Feldspar grains; Flyvbjerg 1; a is microcline and b plagioclase.
a: sample no. 26; b: sample no. 27. ×270.

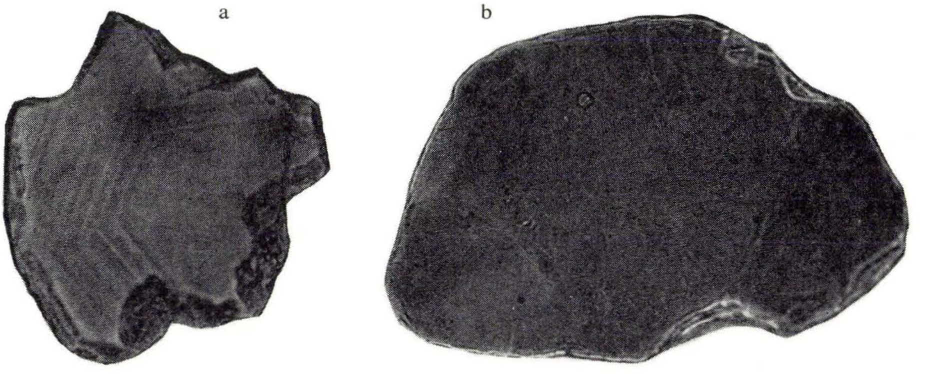


Fig. 25. Examples of mica grains; a is muscovite with zonal structure and b is biotite with a slightly bent border. a: Flyvbjerg 1, sample no. 28; b: Frederikshavn City 1, sample no. 230. ×270.

in amount. Plagioclase grains with refractive indices higher than the index of Canada balsam are seldom found; most grains have refractive indices rather close to the index of Canada balsam. Polysynthetic twinning can be seen in quite a few of the grains. The plagioclase group seems to be mainly represented by albite and oligoclase. A large number of the feldspar grains have subrounded to rounded surfaces and are thus clearly clastic. Others are bounded by cleavage faces without much sign of wear. On some of them there is a feldspathic overgrowth indicating authigenic growth after deposition. The majority of the grains are clear and completely translucent; a small number of grains are clouded and almost opaque, presumably as a result of weathering effects. However, these last-named are, as mentioned, rather rare; the feldspar group seems to be on the whole a rather fresh group of minerals only moderately affected by chemical breakdown.

Mica includes muscovite and brown biotite; in addition there is a green mica, which here and there can occur rather frequently, as for instance in glauconite-bearing horizons, such as the upper glauconitic sequence in Frederikshavn City 1. Muscovite is, moreover, by far the predominant mica. In fig. 25a is shown an example of muscovite with zonal structure, a type that is extremely rare. Biotite occurs as a rule only in small amounts and sporadically; only in one single sample, no. 10 from Vinding 1, is biotite the predominant mica. The smaller mica flakes have as a rule irregular outlines, while the larger flakes have rounded contours and, in many cases, slightly bent margins (fig. 25b), presumably as a result of mechanical wear during the processes of transport and deposition.

Opaque minerals are on the whole the predominant mineral group in the heavy fraction. Even if the opaque grains have not been studied in detail during this investigation, it is nevertheless quite clear that several different minerals are contained in this group. Amongst these, pyrite seems to play an important role, especially in the clayey sediments. Several different morphological types of pyrite occur. One type, which was noted specially during the quantitative investigations, is pyrite in the form of pyritized fossil remains; the remains in question are of agglutinating foraminifera corresponding to those described in the section "Fossil remains", but with a distinctly larger content of pyrite, and also pyrite casts of fossils that were evidently calcareous-shelled. In addition, pyrite occurs as stem-like, bullet-shaped, and completely irregular aggregates, sometimes enclosing grains of quartz and other minerals. In places pyritized plant material is also found. There can hardly be any doubt that the pyrite was formed after the deposition of the sediments. It must be

Fig. 26. Examples of zircon grains. a: Uglev 1, sample no. 20; b: Flyvbjerg 1, sample no. 31; c: Uglev 1, sample no. 17; d: Flyvbjerg 1, sample no. 31; e: Uglev 1, sample no. 24; f: Flyvbjerg 1, sample no. 28; g: Flyvbjerg 1, sample no. 4; h: Lavø 1, sample no. 8; i: Rødby 1, sample no. 22; j: Lavø 1, sample no. 1. ×270. For description see text.

accepted that it formed under reducing conditions – presumably at a very early stage in the course of diagenesis (see LOVE, 1964). Especially in the sandy sediments, opaque minerals are found in the form of more or less rounded, clastic grains; these include magnetite and possibly also ilmenite. In addition, leucoxene is thought to have been detected. Knowledge of these minerals is, however, somewhat limited, since they have not been studied specially during this investigation.

Zircon belongs to the most frequently occurring non-opaque heavy minerals. Several different morphological types are represented; fig. 26 shows some examples. Amongst the types found are idiomorphic grains without a trace of rounding (fig. 26a; fig. 26b shows an idiomorphic double crystal). Others are perfectly rounded (fig. 26h, i). Most of the grains are characterized by some degree of rounding. Some of the grains have zonal structure. In a good many zircon grains there is a fracture pattern in the form of radial cracks extending from the grain centre, which in some cases seems to be developed as an opaque nucleus (fig. 26f); such cracks have presumably arisen as a result of expansion accompanying the metamict alteration of the mineral. In some grains the fracture pattern takes the form of a network of cracks (fig. 26g). Fig. 26e shows an example of a crystal fragment whose fracture surfaces must originally have been radial cracks of the above-mentioned type; several examples of this nature have been observed. About half of the zircon grains are clear and colourless. The rest are mainly brownish, a very few being reddish. Brown coloration is not always a property of the mineral grain, but is sometimes due to a thin superficial skin; this brown skin is translucent, isotropic and may consist of an organic substance. Zircon is more frequently found enclosed in glauconite than are the other non-

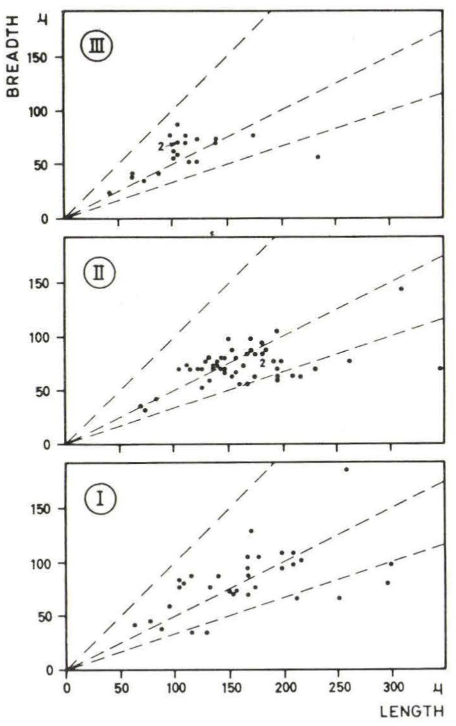


Fig. 27. Frederikshavn City 1; measurements of length and breadth of zircon grains. I: Rhaetic–Lias; II: Dogger–Malm; III: Lower Cretaceous.

opaque heavy minerals; fig. 26j shows an example of this. Furthermore, zircon is also one of those heavy minerals that occur most frequently as an element in the shells of agglutinating foraminifera; in one single example seven small zircon grains were noted. Opaque grains, and also needles that appear to be rutile, are often found as inclusions in the zircon grains. The idiomorphic grains vary very much in form, from short prismatic to long prismatic crystals. An impression of this may be obtained from the diagram in fig. 27, which gives the measurements of length and breadth of over 100 idiomorphic zircon crystals from Frederikshavn City 1. The measurements have been arranged in three stratigraphical groups: I. Rhaetic-Lias, II. Dogger-Malm and III. Lower Cretaceous. It should be noted that the measurements include not only isolated grains, but also some small zircon grains that occur as parts of aggregates. It can be seen from the diagram that elongated zircon crystals occur more frequently in the material from the Dogger-Malm than in the material from the underlying and overlying parts of the sequence. However these observations are based on a very limited amount of material, so that the relation suggested can not really be regarded as geologically significant. Nevertheless the results may indicate that any future detailed studies of the sediments ought to include a more thorough investigation of the zircon. As to the origin of the material, it might at first be supposed that the rounded zircons must stem directly from older sedimentary formations; this is by no means certain, however, since zircon is regarded as not recrystallizing under metamorphism (see, for example, KALSBEEK, 1962). The source of the rounded grains must therefore be considered to be older sediments and/or metamorphosed sediments.

TiO_2-minerals. This group contains rutile, anatase and brookite. Rutile, which is by far the most abundant of these minerals, occurs particularly as single crystals, sometimes with fine twinning lamellae. The grains have varying degrees of rounding, as in the case of the zircon grains. Fig. 28a shows an example of a large idiomorphic rutile grain with twinning lamellae in two directions, evidently (101) and (001). A few geniculate twins occur. An example that is unique amongst the present material can be seen in fig. 28b; it is a cyclic twin composed of four individuals and it is, furthermore, very much worn. Most of the rutile grains are golden brown, some are dark brown with a greyish to violet tint, and a few are foxy in colour. Anatase is very frequently present as more or less square grains (fig. 28f), but other types occur as well (fig. 28e). Only a few are marked by wear in the form of rounding. Most of the anatase grains have a pale, almost silver-grey colour and some are bluish grey; a few dark grains are nearly opaque. Brookite, easily recognizable because of its abnormal interference colours, is a more uncommon mineral than the preceding two. It occurs as a rule in the form of somewhat irregularly bounded grains, often made up of several crystals; definite evidence of rounding was not found. In addition to the types of grain mentioned, the TiO_2-minerals include yet another group of grains, fine-grained aggregates; an example is shown in fig. 28c. This example consists in part of long prismatic grains, which are evidently rutile. Other granular to compact aggregates appear to contain both anatase and brookite. There seems to be a rather smooth transition between these aggregates of translucent TiO_2-minerals and opaque grains that are considered to be composed of leucoxene. As is known, leucoxene is regarded as being an alteration product of ilmenite, and it consists mainly of TiO_2. It is probable that these particular TiO_2-aggregates represent a further stage in this alteration. In support of this possibility, it can be mentioned that ZIMMERLE (1963) describes authigenic brookite crystals occurring as overgrowths on leucoxene grains in Dogger sandstone from Plön in Holstein. During the quantitative investigations a distinction was made between three groups of TiO_2-minerals, namely 1) rutile, 2) anatase + brookite and 3) fine-grained aggregates. As indicated, grains belonging to the last two of these groups are considered to be predominantly authigenic; the rutile grains in the first group are, on the other hand, considered to be largely clastic.

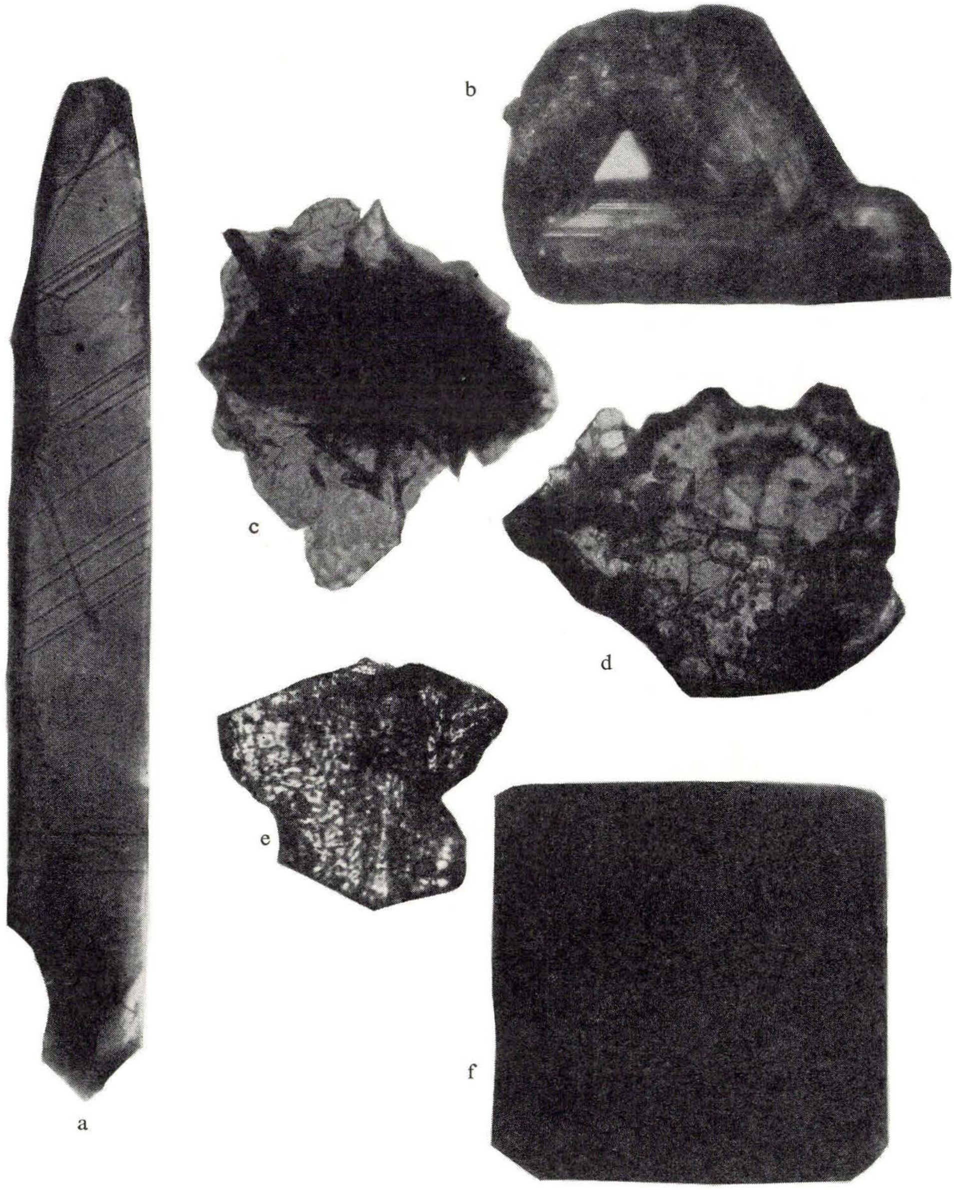


Fig. 28. Examples of TiO_2-minerals; a and b are rutile; c is a fine-grained TiO_2-mineral aggregate; d is brookite, and e and f are anatase. a: Uglev 1, sample no. 15; b: Uglev 1, sample no. 24; c: Flyvbjerg 1, sample no. 28; d: Uglev 1, sample no. 22; e: Frederikshavn City 1, sample no. 221; f: Flyvbjerg 1, sample no. 37. ×270.

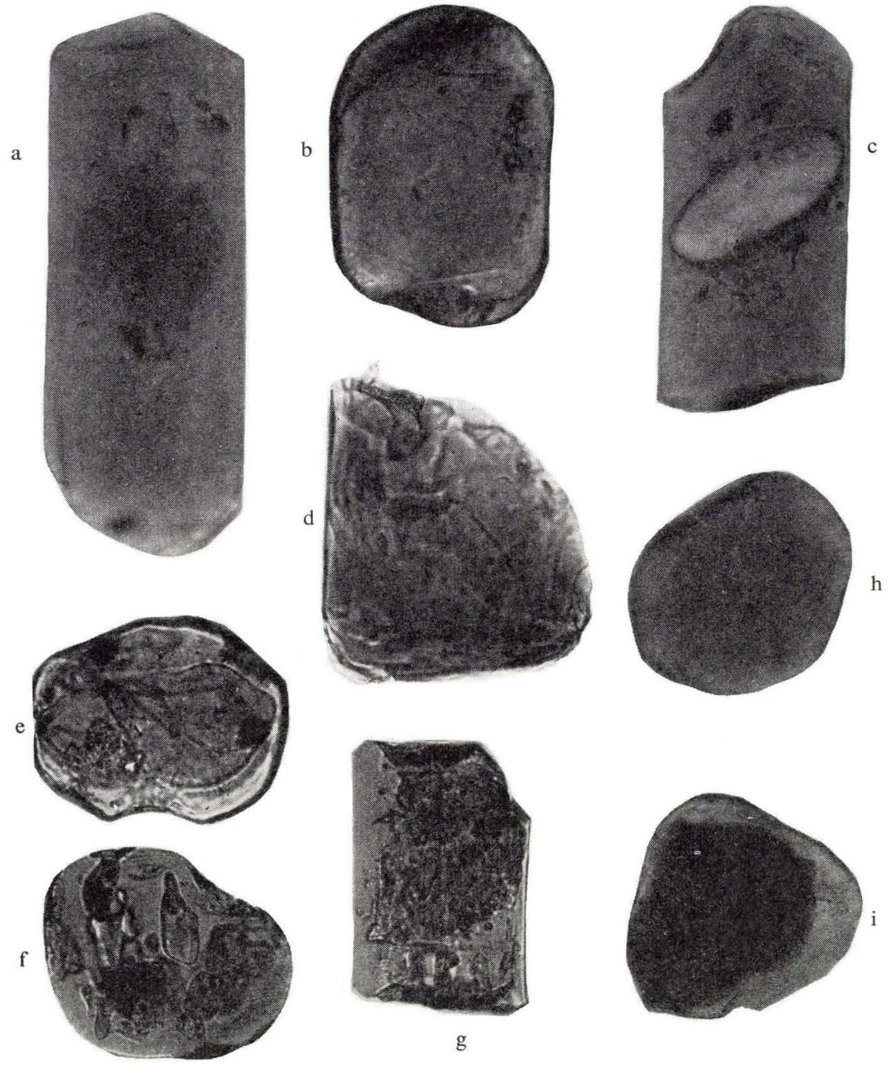


Fig. 29. Examples of tourmaline grains; a, c, e, g and i are of the two-generation type with a more or less well rounded core. a: Uglev 1, sample no. 24; b: Lavø 1, sample no. 5; c: Uglev 1, sample no. 20; d: Lavø 1, sample no. 5; e: Frederikshavn City 1, sample no. 230; f and g: Frederikshavn City 1, sample no. 236; h: Uglev 1, sample no. 21; i: Uglev 1, sample no. 12. ×270.

Tourmaline can be seen to be represented by several different varieties, of which brown and greenish grey are by far the commonest, while, for example, bluish and colourless grains are seldom found. As to grain shape, there are all stages of transition from idiomorphic crystals without any trace of wear to perfectly rounded grains. Some are clearly fragments of larger crystals. Amongst the well rounded grains, brownish types seem to be the most abundant. Some examples of tourmaline grains are shown in fig. 29. A good many of these

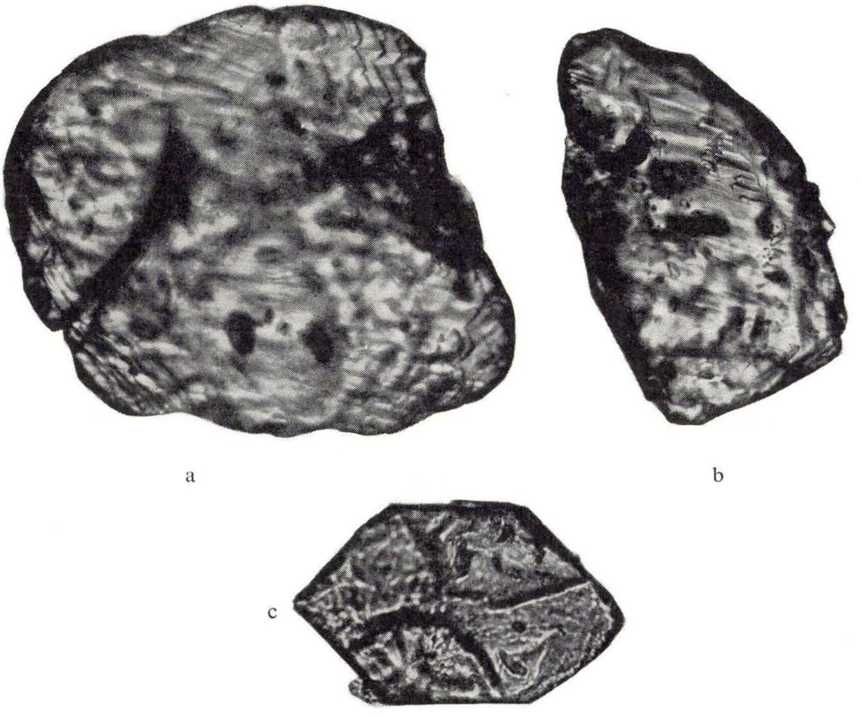
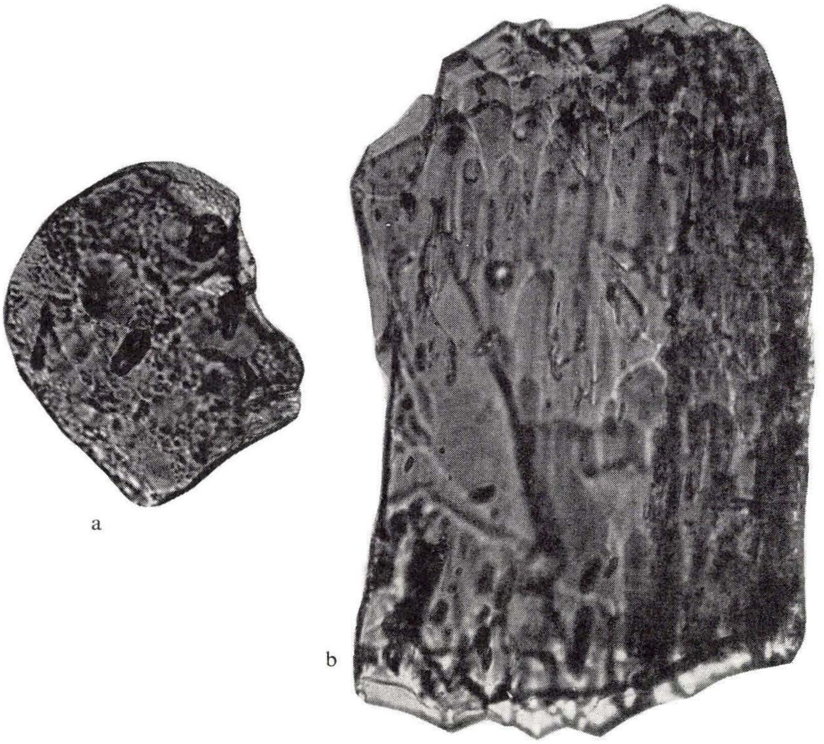


Fig. 30. Examples of titanite grains. a and b: Flyvbjerg 1, sample no. 19; c: Frederikshavn City 1, sample no. 232. ×270.

contain a generally well rounded core of tourmaline with the same optical orientation as the surrounding part of the grain. The core is normally darker than the surrounding material, but a few examples of the opposite are known. The core is undoubtedly an older sand grain; the material round it is probably an authigenic overgrowth (see, for example, PUSTOWALOFF, 1955), which must be referred to an earlier sedimentary stage, since nearly all these double tourmaline grains have subrounded surfaces. Grains of this type are found spread throughout the entire sequence; in places they make up about 10% of the tourmaline grains. It should be noted that comparable grains are known from the Dogger sandstone at Plön in Holstein (ZIMMERLE, 1963). Nowhere were there found any clear indications that authigenic tourmaline formation took place in these particular deposits. The tourmaline grains recorded are therefore regarded for the time being as clastic; many stem presumably from older sedimentary strata.

Titanite (Sphene) is found mainly as more or less worn cleavage fragments; a few grains have remains of crystal surfaces preserved (fig. 30c). Most of the grains are colourless, but a few have a brownish colour and pleochroism. Fig. 30, a and b, show two subrounded to rounded titanite grains on whose surfaces there are etch marks in the form of pits and facets. Since these marks are found on subrounded surfaces, the etching can scarcely be the result of chemical weathering effects before the deposition, but must presumably be attributed to "destructive diagenesis" after deposition. Etched grains of this type are rather abundant.



a

b

Fig. 31. Examples of staurolite grains. a: Rødby 1, sample no. 4; b: Ullerslev 1, sample no. 24. ×270.

Staurolite occurs as yellowish to yellowish brown cleavage fragments with varying degree of rounding. Fig. 31 shows two grains, of which the large one, which is only slightly worn, has coarse etch marks on its surface; the small, well rounded grain has a hummocky surface, which may also reflect incipient dissolution of the mineral. As in the case of titanite, the phenomenon here is probably attributable to diagenetic dissolution. These grains with signs of dissolution are not evenly distributed throughout the sequence; they are clearly specially common in the Ullerslev well, where about 30% of the staurolite grains are etched.

Kyanite, like staurolite, is found in the form of cleavage fragments with varying degrees of rounding and locally with distinct etch marks. Fig 32a shows a large kyanite grain with good rounding, and c a grain of comparable size without rounding but with clear traces of etching. In kyanite also, the etching is considered to have occurred diagenetically. Fig. 32b shows an angular kyanite grain with a few large hollows in the surface; these hollows can not, however, be regarded with certainty as being the result of diagenetic dissolution. These three types are, on the whole, representative of the kyanite grains that are found.

Chloritoid is one of the minerals that occur in rather small amounts. It is found in the form of more or less rounded plates (fig. 33) with the characteristic yellow-green to blue-green pleochroism.

Garnet is one of the main minerals in the non-opaque heavy fraction. Two main types are present, a reddish and a colourless, but there seem to be some transitional types; a few

Fig. 32. Examples of kyanite grains. a: Frederikshavn City 1, sample no. 225; b: Frederikshavn City 1, sample no. 223; c: Ullerslev 1, sample no. 25. ×270.

greenish, isotropic grains are also considered to be garnet (uvarovite?). A few of the grains are idiomorphic (fig. 34b, c). Most of the grains are irregular fragments with varying degrees of rounding. Fig 34a shows a large fragment with only slight traces of rounding, while d is a perfectly rounded grain (d is one of the greenish grains whose identity is in doubt). Etching phenomena are present on quite a number of the grains; fig. 34 shows two examples. The grain in fig. 34c is rather lightly etched, so that the resulting fine facets only slightly obscure the well developed crystal surfaces of the grain. A more thorough dissolution has evidently affected the garnet in fig. 34e, where there is hardly anything left of the original surface of the sand grain; the etching of the garnet is also considered to be a

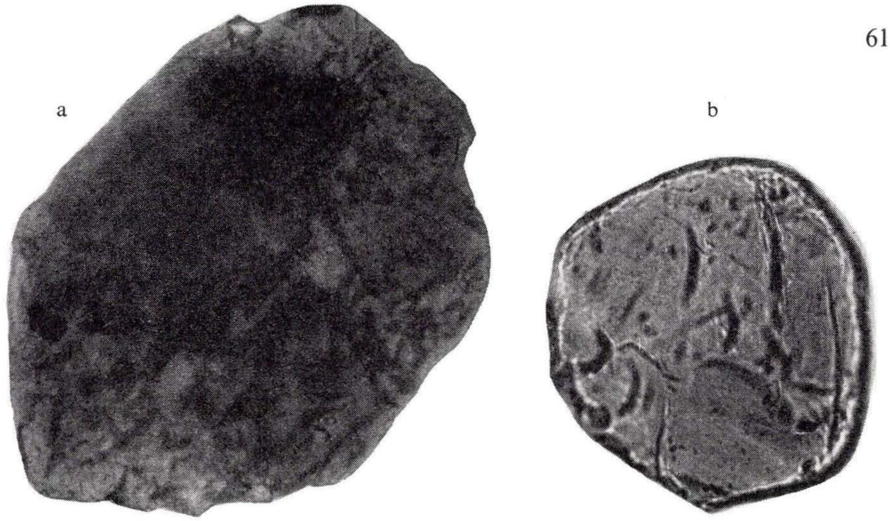


Fig. 33. Examples of chloritoid grains. a: Flyvbjerg 1, sample no. 31; b: Lavø 1, sample no. 8. ×270.

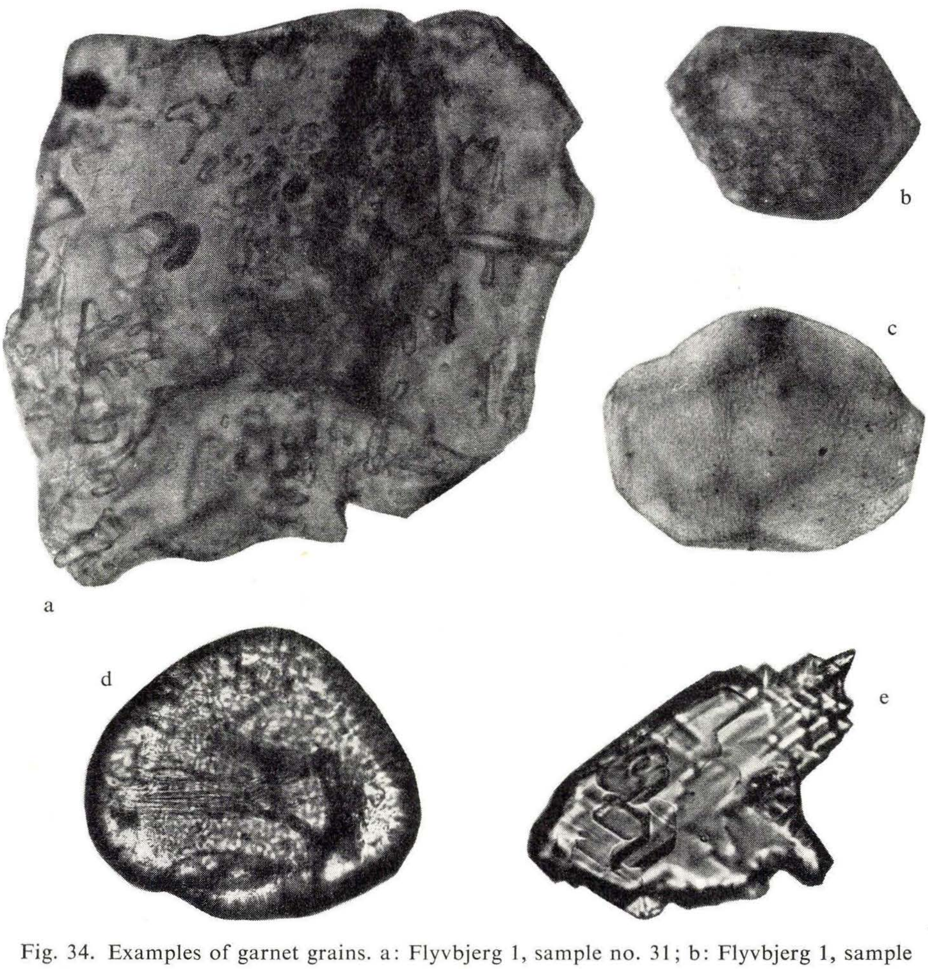


Fig. 34. Examples of garnet grains. a: Flyvbjerg 1, sample no. 31; b: Flyvbjerg 1, sample no. 30; c: Uglev 1, sample no. 12; d: Lavø 1, sample no. 8; e: Lavø 1, sample no. 1. ×270.

diagenetic phenomenon. It should finally be noted that a garnet type corresponding closely to the one in fig. 34e has been described from the Yorkshire Dogger as "cleaved garnet" (RASTALL & HEMINGWAY, 1940).

Epidote is a general term covering the minerals pistacite, clinozoisite and zoisite. Amongst these, the greenish yellow pistacite is by far the most common. Most grains are cleavage fragments of single crystals; only a few consist of fine-grained aggregates. The degree of rounding varies, most of the grains being moderately to well rounded, which can be seen in the grains in fig. 35. One single grain (b) is rather strongly affected by dissolution, which presumably has taken place diagenetically. Grain (c) is possibly also weakly affected by diagenetic dissolution, but in this case the features are harder to interpret. It can thus be seen from the observations that epidote grains with signs of diagenetic breakdown do occur, but it is remarkable how rarely these are present considering that epidote is generally regarded as being one of the more unstable minerals. From fig. 35 it can be seen that rounded epidote grains without signs of dissolution occur not only in the sediments near the margin of the basin, but also in the deposits from the deeper part of the basin (e, g).

Amphibole is mainly represented by green to blue-green hornblende; a few grains of actinolite were found. The amphiboles occur as cleavage fragments, often with good rounding of the edges. Like epidote, amphibole is regarded as being one of the unstable minerals, and there exist in the literature several descriptions of signs of dissolution, such as the formation of jagged crystals ends, in these minerals (e.g. EDELMANN and DOEGLAS, 1932; SLATKINE and POMERANCBLUM, 1958). However, so far as can be seen, such signs or other indications of chemical breakdown are not present in the material examined. The examples shown in fig. 36 are typical so far as the state of the grains is concerned.

Pyroxene is present in rather small amount; it is represented by greenish augite and hypersthene. The latter mineral seems to occur most commonly at Skagen and Frederikshavn. The grains vary in degree of rounding from subangular to rather evenly rounded. Clear evidence of dissolution was not detected.

"Other minerals" is a heading in the diagrams under which there are recorded certain minerals whose identity has not been determined with certainty. A dark red-brown, isotropic mineral with high refractive index is believed to be spinel. Corundum is possibly represented by grains that take the form of irregular fragments with greyish blue colour, high refractive index and low birefringence. Some colourless, optically uniaxial negative grains with high refractive index and low birefringence are assumed to be idocrase (vesuvianite). A few colourless, fibrous, anisotropic grains with refractive indices a little above 1.66 are possibly fibrolite (sillimanite). The grains mentioned here all occur in rather small amounts; in most of the samples they make up less than 1% of the non-opaque heavy-mineral fraction.

"Remarks" is another heading in the diagrams. Under this is recorded the occurrence of certain minerals that are not included in the quantitative investigations. Amongst these is *barytes*, which, as far as can be seen, is an authigenic mineral (see, for example, HADDING, 1939). Examples of barytes grains are shown in fig. 37. These grains are single crystals containing some remains of the original sediment; grains a and b are clearly casts of tests of foraminifera. Barytes is also found locally in the form of stem-like aggregates. Another

Fig. 35. Examples of epidote grains. a: Ullerslev 1, sample no. 25; b and c: Frederikshavn City 1, sample no. 230; d: Skagen 2, samples nos. 93 + 94; e: Haldager 1, sample no. 63; f: Børglum 1, sample no. 7; g: Gassum 1, sample no. 579. ×270.

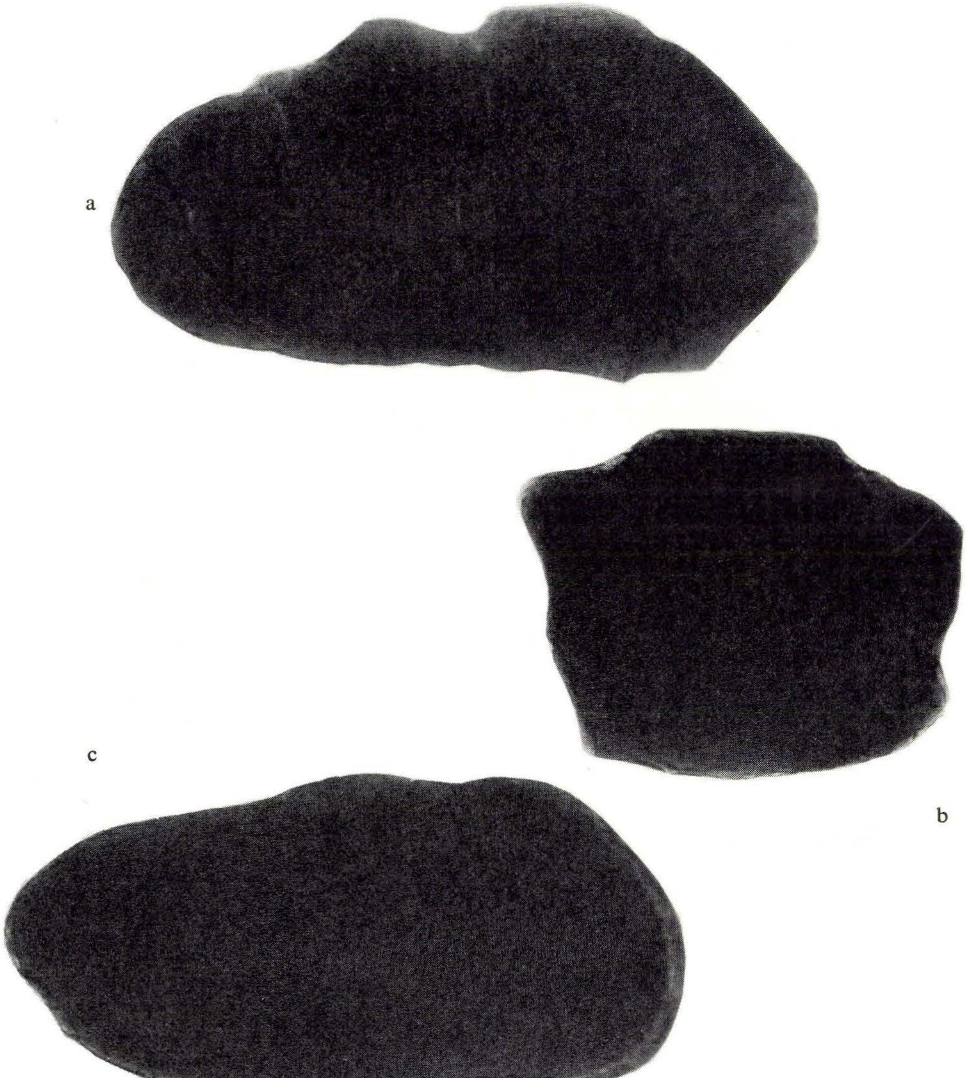


Fig. 36. Examples of hornblende grains. a: Uglev 1, samples no. 11; b and c: Skagen 2, samples nos. 93 + 94. ×270.

component is *phosphorite*, some characteristic examples of which are shown in fig. 38. There are two types of phosphorite grain, a brown, fibrous type with clear remnant structure from organisms (fig. 38a, b), and a brownish, isotropic, presumably amorphous type, which is present as spherical or lobate aggregates (fig. 38c). The former type can be seen to include some rounded fragments of phosphoritized shells of organisms, and must therefore be regarded as clastic; the latter type, which, as far as can be seen, is not marked by wear, is considered to have been precipitated authigenically. Phosphorite is found in

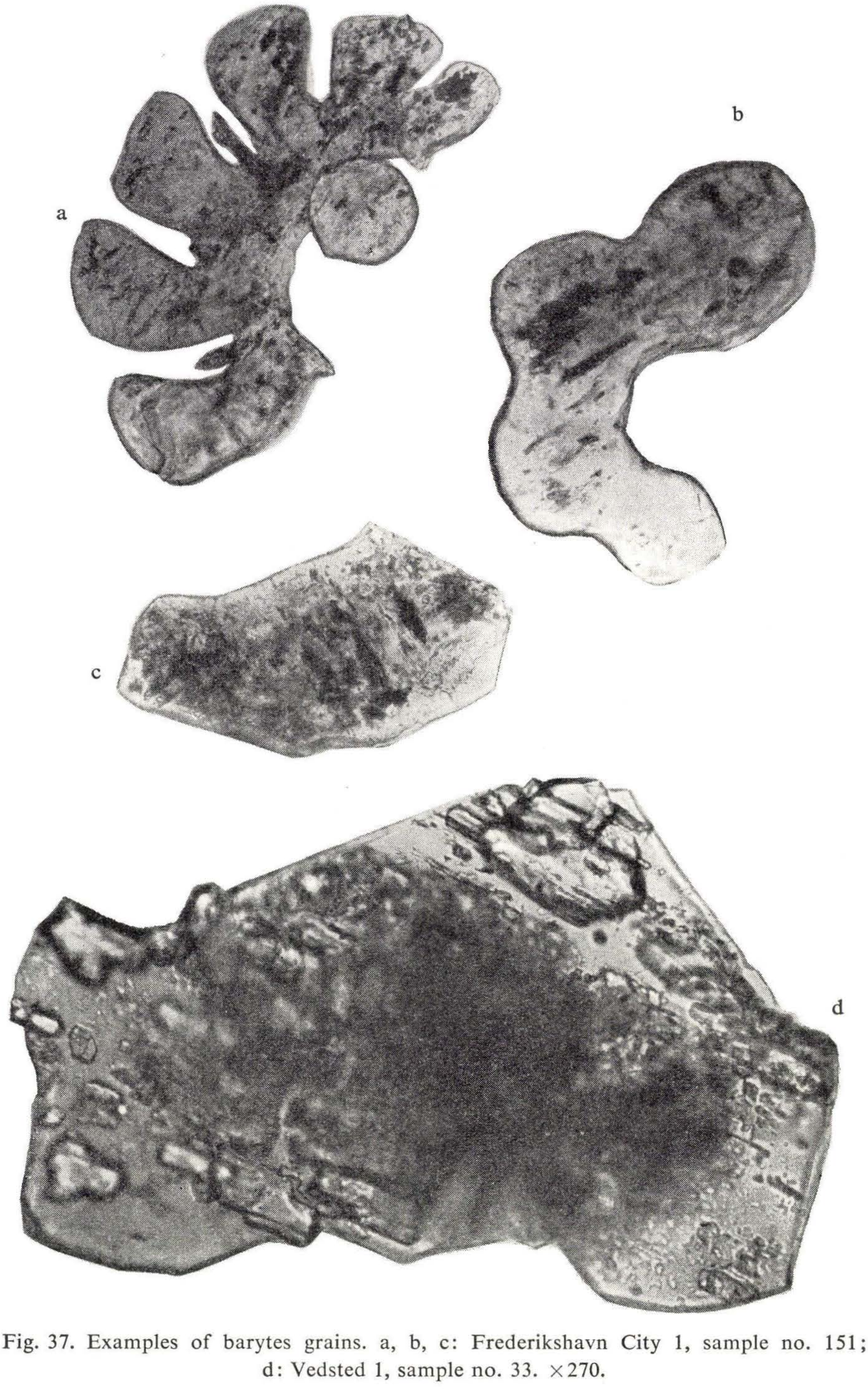


Fig. 37. Examples of barytes grains. a, b, c: Frederikshavn City 1, sample no. 151; d: Vedsted 1, sample no. 33. ×270.

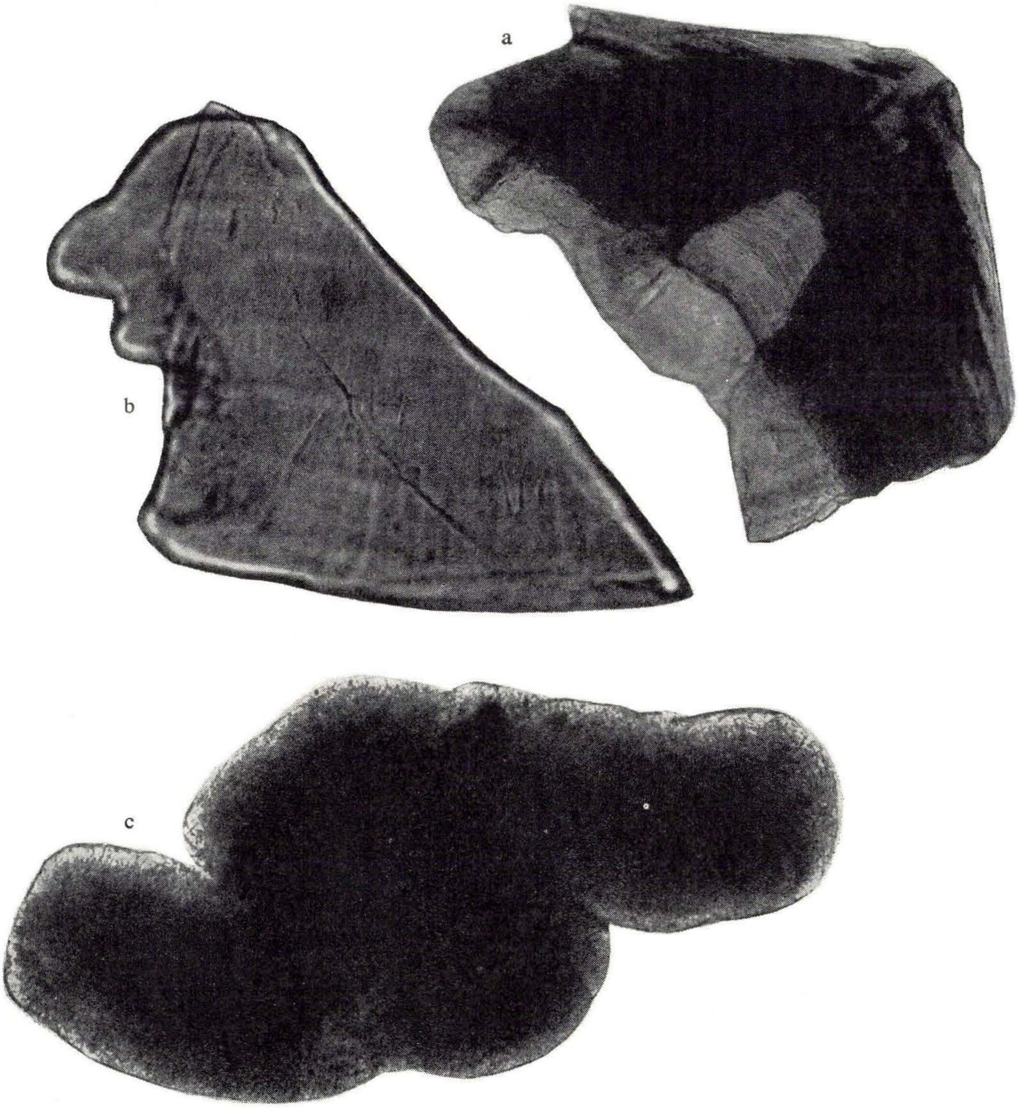


Fig. 38. Examples of phosphorite grains; Rødby 1, sample no. 2. a and b consist of fibrous, anisotropic phosphorite with structure inherited from former organisms, c consists of amorphous phosphorite. a: ×110; b and c: ×270.

small amounts here and there, but is only a dominating element in one sample, no. 2 from Rødby 1. This sample appears to represent the Albian transgression bed, which rests on the Lias. A third type of mineral is *siderite*, which occurs partly in the form of aggregates with radial structure. Finally there is a mineral that has not yet been identified (x). It is isotropic with a high refractive index (> 1,66) and a golden colour resembling that of rutile. Because of the somewhat irregular but distinctly angular grain boundaries it is considered that the mineral is authigenic.

In the preceding comments special attention was paid to such aspects of the properties of the minerals and aggregates as are regarded as being important in assessing these as components of the sediments. It is therefore considered to be of some importance to try to distinguish between the clastic and the authigenic components, and furthermore in the case of the clastic components, to throw light on the possible influence of destructive diagenesis. Knowledge of these factors is of critical importance in assessing the reasons for the mineral distribution found during the quantitative investigations.

SOME FEATURES OF THE MINERAL DISTRIBUTION

It can be seen from the diagrams (Plates II–XVII) that there are significant differences in the mineral distribution between one area of the basin and another, for example between the borings in north Jylland and those in Fyn, Sjælland and Lolland.

It must be added here that it is of course a precondition for being able to attach geological significance to differences and similarities in the mineral distribution, that the analytical results from the individual borings and samples can be taken as representative and reproducible. Investigation of the borings in Øresund has thrown some light on this question. Two of these borings, nos. 8 and 9, contain the same stratigraphical sequence, namely the Döshult sandstone of age Lias alpha-3. The distance between these borings was ca. 300 m. Analyses of samples from the two boreholes showed that, so far as the main features of the quantitative mineral distribution were concerned, there was good correlation between the wells, in that samples from the same bed in the two borings had approximately the same mineral content (LARSEN et al., 1965). This indicates that the reproducibility is good, which agrees very well with the results of the author's earlier examination of the mineral content of some Danish Tertiary deposits (LARSEN and DINESEN, 1959). During the same Øresund investigations it also became apparent that in certain parts of the geological section significant changes take place in the relative amounts of the minerals within small vertical distances. Comparable evidence was obtained from other areas during the present investigations. This must mean that a study must include a series of samples rather close to each other if its results are going to be regarded as representative for the particular section. As mentioned in the introduction, the wells in this account constitute study material that is very heterogeneous in quality. The boreholes from which there are reasonable good series of samples are all situated in the neighbourhood of the margin of the basin; the wells in question are Skagen 2 and Frederikshavn City 1 on the northern margin and also Ullerslev 1 and Rødby 1 near the boundary with the Ringkøbing-Fyn High. To these can be added the Øresund borings, which, at any rate in part of the sequence, have very good sample material. Of the boreholes in the more central part of the Danish Embayment, Gassum 1 is that which has, for the sequence as a whole, the best series of samples. Certain sections of the sequence are also rather well represented in Haldager 1 and Uglev 1, while from the remainder of the boreholes there is only a rather limited and scattered collection of analytical material.

This lack of uniformity in the representativeness of the sample material must be kept in mind during the following treatment of the main features of the mineral distribution in the area of the investigation. Mention will be made first of the wells Skagen 2 and Frederikshavn City 1, from which, as stated, there is good material. Then follows an examination of the remaining borings in Jylland together with evaluations of possible similarities between these and the two boreholes in north Jylland. Ullerslev 1 and Rødby 1 are commented on next. Finally the Øresund occurrence, and in this connection Lavø 1, will be discussed.

Skagen 2 – Frederikshavn City 1 (Plates II and III)

The distance between these wells is ca. 30 km. As mentioned earlier, on the lithological-stratigraphical side, it has been possible to establish a reasonably good correlation; the most important difference stratigraphically seems to be that the Rhaetic at Skagen is greatly reduced in thickness compared with the occurrence at Frederikshavn, and especially that the upper, marine part (Vedsted Formation) of the Lower Cretaceous is absent at Skagen.

If the analytical diagrams are compared it can be seen that there are considerable similarities on the petrographical side, but that there are, nevertheless, distinct differences in certain respects.

A few remarks will be made first about the distribution of remains of organisms and about glauconite. In both the wells remains of organisms (mainly foraminifera) occur very commonly in the Lower Jurassic, and in both borings glauconite is present in the Upper Jurassic. Some difference can be detected as well, however, in that glauconite occurs less frequently at Skagen than at Frederikshavn. In this connection reference is made to the fact mentioned in an earlier section that some of the glauconite grains in the Upper Jurassic at Skagen are covered with opal, whereas this is apparently not true of the Upper Jurassic glauconite at Frederikshavn. On the other hand, opal is found here in connection with the few and scattered glauconite grains in the Dogger deposits; the Dogger in Skagen 2 is apparently not glauconite-bearing. It can be seen from the diagram for Frederikshavn City 1 that the Lower Cretaceous deposits here are much richer in glauconite than the previously mentioned Upper Jurassic deposits, and that the glauconite occurs in well defined horizons separated by glauconite-free horizons. The uppermost of these glauconite horizons is, as stated, organism-bearing (see also fig. 17). The limonite-coloured bed mentioned earlier (p. 44), in which there is opal with remains of glauconite, is situated at the bottom of the upper glauconite horizon. It is also appropriate to mention that plant material is found in both borings in varying amounts in all parts of the sequence, i.e. not only in the obviously non-marine beds. For example, the marine Lias deposits contain rather a lot of plant material.

The course of the curve for the quartz/feldspar ratio has the same general pattern in the two wells, relatively low values in the Rhaetic and the basal part of the Lias, a very large and strongly developed maximum in the Lower Dogger and a second comparable maximum in the Lower Cretaceous Skagen Formation. It can also be seen that this agreement in the course of the curves is at any rate partly independent of grain size. This emerges very clearly in the Dogger beds, since these are significantly finer-grained in Skagen 2 than in Frederikshavn City 1. The points of similarity between the wells are striking, but there are also differences. For example the two zones with a high quartz/feldspar ratio are distinctly thicker at Skagen than at Frederikshavn, a feature that is reflected by the fact that the position of the Lower Jurassic/Middle Jurassic boundary in relation to the lower zone is not the same in the two wells. The course of the curve between the large maxima oscillates very much in each well, with many small maxima and minima, but it has not proved possible to correlate with certainty the details in the pattern of the curve from well to well.

So far as the non-opaque heavy-mineral distribution is concerned, one of the features that the two wells have in common is that garnet is a common component in the lower part of the succession, including also the Keuper arkoses. Titanite is likewise a characteristic mineral in these beds, even if it is not usually found as frequently as garnet. In a section of the Dogger corresponding to the lower of the quartz/feldspar maxima, the curve for garnet content shows the same characteristic course in both wells; this section seems to be a rather well defined marker horizon. In Skagen 2 epidote is the predominant non-opaque heavy mineral in the sequence as a whole. The course of the epidote curve oscillates very much between very high and very low values. In Frederikshavn City 1 also, epidote is the predominant heavy mineral throughout large parts of the Lower Cretaceous, while it is not so prominent in the deeper parts of the sequence. As at Skagen, the epidote content falls into a series of marked maxima and minima. In the same way that it was possible to trace a distinct correlation between the lower large quartz/feldspar maximum and the course of the curve for garnet in the same section, it is quite evident that there is a correlation to be found in the section of the epidote curve corresponding to the upper large quartz/feldspar maximum; the quartz/feldspar maximum is thus matched by an epidote minimum, which is bounded both upwards and downwards by marked maxima. The other large variations in the epidote content do not, however, appear to be correlatable with certainty from well to well. Hornblende is found here and there, but mainly in small amounts. In Skagen 2 the content of hornblende is greatest in the lower part of the sequence.

A preliminary inspection of the diagrams suggests that there could be a certain mutual relation between the course of the curves for epidote content and tourmaline content respectively. In order to find out whether such an agreement really existed, the amount of tourmaline was recalculated as the percentage of tourmaline in the non-opaque heavy-mineral fraction without epidote. This expression of the amount of tourmaline was then compared with the epidote percentage with the results shown in fig. 39. It emerges from this that no clear link between these components can be shown for the material as a whole, but in certain parts of the sequence it was found that a high epidote content is matched by a low tourmaline content.

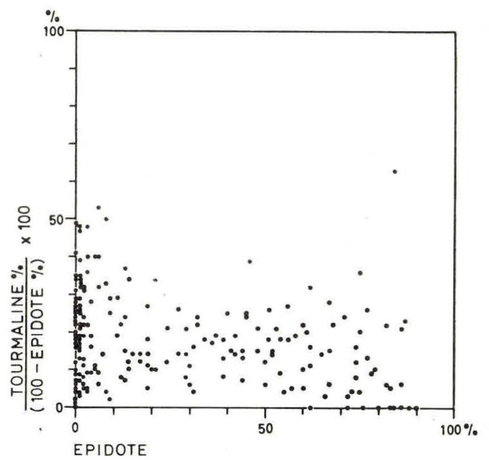


Fig. 39. Frederikshavn City 1, and Skagen 2. The relation between the epidote content on the one side and on the other the content of tourmaline in the non-opaque, non-micaceous heavy-mineral fraction minus epidote.

In addition a tendency has been noted for the content of staurolite + kyanite to be rather large in certain parts of the sequence where the quartz content is high and the epidote content low. The relative amounts of staurolite and kyanite are illustrated in the diagram fig. 40. It can be seen from this that in both wells kyanite is the predominant mineral in most of the samples; however, there is a numerical difference, namely that in Skagen 2 kyanite is predominant in three quarters of the samples, while this only applies to two thirds of the samples in Frederikshavn City 1.

As to the stable minerals (zircon, rutile, tourmaline) it seems as if there is some difference between the wells; these minerals are thus generally more abundant at Frederikshavn than at Skagen, at any rate in the Rhaetic-Jurassic; this can also be sensed in the diagram fig. 41, which gives the relative amounts of zircon and tourmaline. The reason that this diagram deals with these two stable minerals in particular is that they are regarded as being definitely clastic, while rutile is evidently authigenic in certain cases. This difference in the content

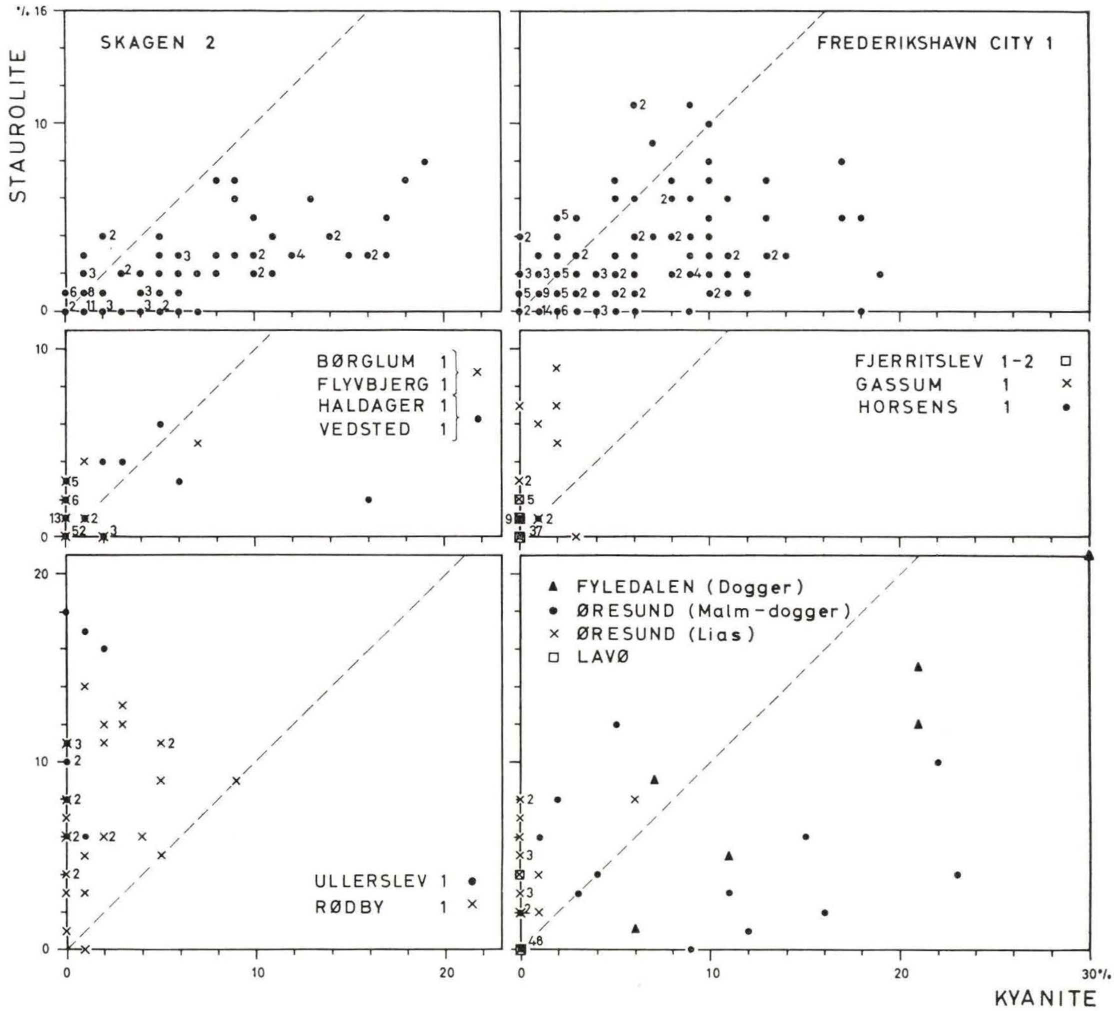


Fig. 40. The relation between the staurolite content and the kyanite content.

of the stable minerals must be seen in direct connection with the larger amounts of epidote in Skagen 2.

These comments on the Skagen and Frederikshavn profiles can be rounded off and summarized in the following general characterization of the clastic mineral assemblage. In both wells the sequence is marked by an "immature" mineral association, whose characteristic minerals are feldspar and epidote as well as garnet in the deeper parts. Mixed with this is a more "mature" association with a higher content of quartz and stable heavy minerals.

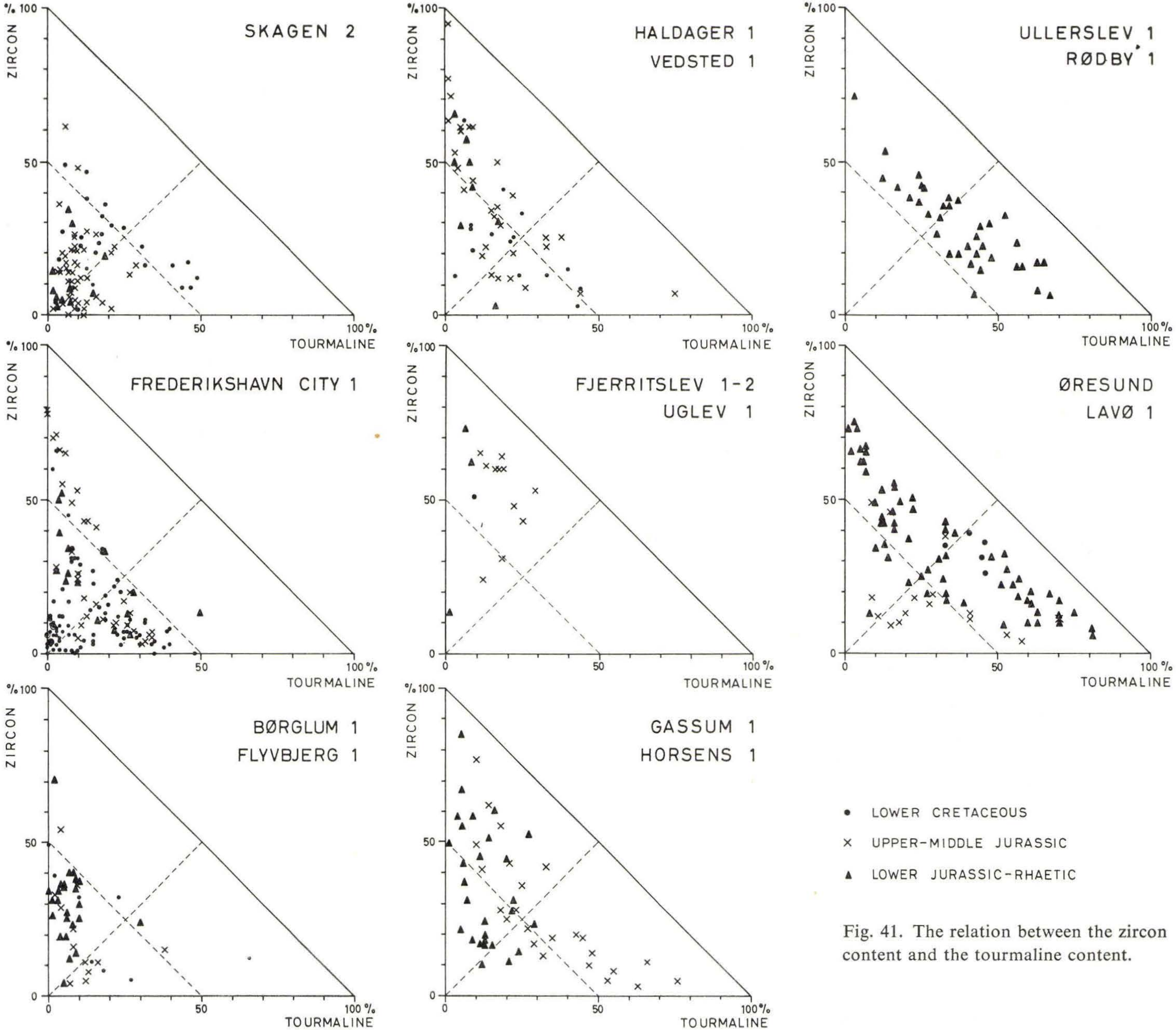


Fig. 41. The relation between the zircon content and the tourmaline content.

Børglum 1 and Flyvbjerg 1 (Plates IV and V)

Børglum 1 and Flyvbjerg 1 are the nearest borings to the south; they are situated at a distance of ca. 30 km from Frederikshavn, i.e. roughly the same distance as from Skagen to Frederikshavn. Lithologically and stratigraphically there is a good correlation between Frederikshavn City 1 and these two wells. There are scattered samples from the whole of the sequence in Børglum 1, while the Lower Cretaceous is not represented in the sample material from Flyvbjerg 1. The petrography of the beds can therefore only be sketched rather roughly.

As to the glauconite content, as at Frederikshavn this mineral is present in the Lower Cretaceous and the Upper Jurassic and in addition at the very top of the Dogger. Nowhere, however, was glauconite detected in such large concentrations as at Frederikshavn.

In Børglum 1, the quartz/feldspar curve shows a course that seems to be correlatable with the comparable curve for Frederikshavn City 1; there is, for instance, a maximum in the Dogger and another in the basal part of the Lower Cretaceous. To what extent the correlation suggested really exists can not be determined with certainty; it is evidently not valid for Flyvbjerg.

In the upper parts of both wells there is some content of epidote as in the two northern wells, but the percentages are lower throughout here. On the other hand, in a single sample from the top of the Lias in Flyvbjerg 1, there is a higher content of hornblende than was detected in the previously mentioned wells. Garnet occurs in varying amounts: a weak tendency can be traced for the amounts to be greatest in the lower part of the sequence as was the case at Skagen and Frederikshavn. The content of staurolite and kyanite is very low, and compared with Frederikshavn and Skagen there is this difference that the staurolite exceeds kyanite in amount (see fig. 40). The stable minerals are, on the whole, rather prominent in the heavy-mineral assemblage. The ratio zircon/tourmaline is generally biased in favour of zircon, a feature that is most pronounced in the case of the Rhaetic – Liassic beds (fig. 41).

It can be seen from this account that the immature epidote- and garnet-bearing association described from Skagen and Frederikshavn can be clearly traced in these wells also, but it is evidently not so prominent as in the two northern wells.

Haldager 1 and Vedsted 1 (Plates VI and VII)

These borings are, in turn, situated ca. 30 km south of the previous two. On the lithological-stratigraphical side Haldager 1 fits well with the two borings just described, except that the borehole at Haldager was not continued as far as the Rhaetic. Vedsted 1, on the other hand, was continued to this level, but this well differs from the Haldager well and those to the north in that the sandy Lower Cretaceous Skagen Formation is not present. In Haldager 1 the transition between the Lower Cretaceous and the Upper Jurassic is well represented in the sample material, while from the remainder of the sequence as well as from the whole of the Vedsted section, there are only scattered analytical samples.

Just as in the wells described previously, there is in these two wells a glauconite content in the Lower Cretaceous and the Upper Jurassic while the rest of the Jurassic is evidently not glauconite-bearing. As to remains of organisms, these two borings have a higher content in the Lower Cretaceous and Upper Jurassic than was the case in the wells farther north.

The curve for the ratio quartz/feldspar is relatively smooth and shows rather low values in the transition beds between the Jurassic and the Cretaceous in Haldager 1; the characteristic large maximum that was found in the basal Lower Cretaceous at Skagen and Frederikshavn and possibly also at Børglum is thus entirely absent at Haldager. In the Dogger there are both high and low values in these two profiles, but as the samples are very scattered it is hardly possible to decide whether there is here a development matching that shown in the two wells farthest north. In the Vedsted profile the feldspar content is rather large in the Rhaetic beds as in all the four northern wells.

Amongst the non-opaque heavy minerals, epidote plays an even smaller role than in the borings at Børglum and Flyvbjerg. In the Lias in Haldager 1 it was found that there was a somewhat higher content of hornblende in connection with a lower content of epidote; it is possible that this occurrence matches the rather hornblende-rich occurrence that, as mentioned, is found in the Lias in Flyvbjerg 1. Neither epidote nor hornblende is markedly affected by etching. Garnet is also found mainly in small amounts; only a few samples have a larger content. It is to be noted that the garnet content in the Rhaetic at Vedsted is significantly lower than in the comparable beds in the wells farther north. The garnet grains are nearly all strongly etched in this deposit at Vedsted. As at Børglum and Flyvbjerg, the minerals staurolite and kyanite are on the whole subordinate components, and as in those wells the ratio staurolite/kyanite is generally biased in favour of staurolite (fig. 40). The stable heavy minerals are certainly predominant in the sequence as a whole. If the content of tourmaline and zircon is considered (fig. 41), it will be noticed that zircon is predominant in the Rhaetic – Lias as at Børglum and Flyvbjerg; in the rest of the succession the distribution is more mixed.

In summary it can be said about the clastic mineral assemblage in these two wells that it appears to fit very well into the development that has been traced from Skagen–Frederikshavn through Børglum and Flyvbjerg; i.e. the unstable, epidote and garnet association becomes less and less prominent southwards where instead a stable association becomes predominant.

Fjerritslev 1 and 2, and Uglev 1 (Plates VIII, IX, X)

These lie to the west and south-west of the wells previously described. In Fjerritslev 2 the ca. 2 km thick sequence evidently represents the whole of the Rhaetic – Jurassic – Lower Cretaceous. This section differs lithologically from those mentioned previously in that neither in the Rhaetic nor in the Upper Jurassic and Lower Cretaceous is any real sand facies found to be developed; on the other hand, a section of the Dogger is sandy as in the other wells. The Fjerritslev no. 1 section is strongly reduced in thickness compared with that of no. 2, but apart from this it does not seem to differ fundamentally from it on the lithological-stratigraphical side. Uglev 1 is situated ca. 70 km from the Fjerritslev borings. At this locality there is a salt dome, and presumed Dogger rests directly on the cap rock, i.e. the Rhaetic and the Lias are absent here. The Dogger, Malm and Lower Cretaceous are lithologically rather similar to the occurrences at Fjerritslev, the Dogger being sandy and the overlying deposits mainly clayey.

Glauconite is found locally in the Lower Cretaceous at Fjerritslev, but has not been detected at Uglev. On the other hand remains of organisms are found in considerable amounts in the Upper Jurassic and the Lower Cretaceous at Uglev; the same applies to the Lower Cretaceous and Upper and Middle Jurassic at Fjerritslev, whereas the content in the Lias beds is clearly much more modest.

The quartz/feldspar ratio is very high in the sandy Middle Jurassic beds in Uglev 1, a feature that fits very well with the results from Skagen 2 and Frederikshavn City 1. In the rest of the sequence at Uglev and in the Fjerritslev borings the quartz/felspar ratio is low to moderate.

Amongst the non-opaque heavy minerals epidote and hornblende play virtually no role; only a few grains were observed in the Dogger at Fjerritslev and in the Lower Cretaceous at Uglev. It should be noted that these few grains are without visible etch marks. In a single sample from the Lias in Fjerritslev 1 there is a very high content of garnet, but in all other samples the content was very low. Staurolite and kyanite are likewise very rare, and are evidently totally lacking in the section in Uglev 1; it can be seen in fig. 40 that staurolite is the predominant of the two minerals. When the one garnet-rich sample in Fjerritslev 1 is disregarded, the stable minerals are entirely predominant in the material; zircon is the main mineral here (see fig. 41).

It therefore appears that the main features of the mineral assemblage in these wells in the deeper, relatively central part of the Danish Embayment are the scanty epidote content and the high content of stable heavy minerals. These features fit naturally into the change in the mineral assemblage outlined earlier, a change that can be traced from the northern marginal area of the basin towards the south and south-west out into the basin.

Vinding 1 (Plate XI)

Vinding is situated in a relatively isolated position. In this well the Rhaetic, Lias and beds presumed to be Dogger, as well as the Lower Cretaceous, are developed as marine, predominantly clayey facies; the Malm is evidently not represented. There are only scattered samples from this sequence.

A small content of glauconite was found in the presumed Dogger beds.

Remains of organisms are present in considerable amounts in all parts of the sequence.

The quartz/feldspar ratio is mainly low to moderate. Since the deposits are mainly clayey, it is not surprising that non-opaque heavy minerals in the fraction 75–250 μ are so rare that no basis was found for making a calculation of the amounts in per cent of the various minerals. In the Lower Cretaceous zircon seems to be the most prominent mineral. In the upper part of the Rhaetic garnet and hornblende are found; in the lower part titanite is the only mineral of this group found until now. This last fact is a special feature, which is reminiscent of the boring Harte 2. Here, according to GRY (1948), titanite is the most characteristic mineral in strata that, according to CHRISTENSEN (1962), belong to the Rhaetic. This feature may indicate that the mineral content in the well Vinding 1 should be regarded more in the light of conditions prevailing in the area of the Ringkøbing-Fyn High than in the light of those existing in the northern marginal area of the basin.

Gassum 1 – Horsens 1 (Plates XII and XIII).

These wells are situated, as were those previously mentioned, in the more central part of the Danish Embayment, but at a position somewhat more to the east. In both, the succession is incomplete stratigraphically; in Gassum 1 the Dogger is absent and in Horsens 1 the Upper Jurassic and most of the Lower Cretaceous are missing. Only a few samples are available from Horsens while Gassum 1 is represented by a rather good series of samples.

In Gassum 1 there is a rather high content of glauconite in samples from the Malm and the Lower Cretaceous. It will be recalled that this was also true of the borings in north Jylland. Remains of organisms are encountered almost everywhere in the Lias and also at a few places in the Rhaetic and Malm, as well as in the Lower Cretaceous.

The quartz/feldspar ratio is mainly low in the Rhaetic in both borings, as it was in the borings in north Jylland. In the Lias the values vary rather strongly. The Dogger in Horsens 1 has very high values as in Skagen 2, Frederikshavn City 1, Uglev 1 and possibly several others. The Upper Jurassic and probably also the Lower Cretaceous have rather varying values for the quartz/felspar ratio.

Knowledge of the non-opaque heavy-mineral content is, naturally enough, based especially on the sandy formations, i.e. the Rhaetic, Dogger and Malm. One fact that emerges is that the minerals epidote and hornblende play virtually no role at all. On the other hand, garnet is one of the characteristic minerals, especially in the Rhaetic. In Gassum 1 garnet is especially common in the lower part of the Rhaetic, where the amount of the mineral is in places 75% of the non-opaque heavy-mineral content. It should be noted that there is obviously a correlation between the garnet content and the quartz/feldspar ratio; the samples richest in garnet are also the richest in feldspar. This relation is ex-

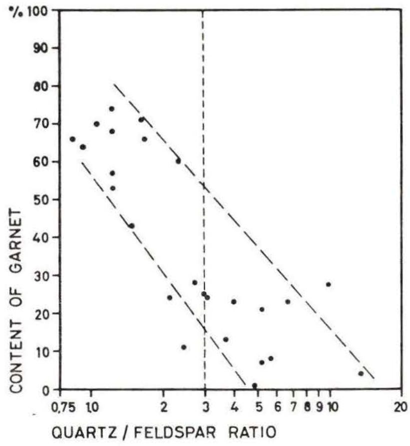


Fig. 42. Gassum 1; the relation between the garnet content and the quartz/feldspar ratio for Rhaetic sediments.

pressed in the diagram fig. 42. A correlation of this nature evidently does not apply to the Upper Jurassic beds in Gassum 1. Staurolite and kyanite do not play any role where amount is concerned. Staurolite is the more abundant of the two (see fig. 40). In the Rhaetic beds in both wells zircon is, on the whole, predominant in amount over tourmaline (fig. 41); this corresponds to what was found in Børglum 1, Flyvbjerg 1, Haldager 1, Vedsted 1 and Fjerritslev 2. In the Upper Jurassic, in some cases it is zircon that is predominant, in others tourmaline, in the same way as, for example, in Haldager 1. In Gassum 1 there seems to be some agreement between grain size on the one hand and the ratio zircon/tourmaline on the other since the coarsest beds are the richest in zircon.

It can be seen from these few remarks that the wells Gassum 1 and Horsens 1 can obviously be correlated to some extent petrographically with the wells situated to the north.

Ullerslev 1 and Rødby 1 (Plates XIV and XV)

These two wells are situated on the flank of the Ringkøbing-Fyn High. The well sections consist of Rhaetic in the first well and Rhaetic-Lias in the second; in addition, the youngest Lower Cretaceous is present in both in the form of the Rødby Formation. Rather good series of samples are available from both borings.

One of the features that can be seen from the diagram showing the main components of the light fraction is that the Lias in Rødby 1 contains rather a lot of plant material even if the marine character of the deposit is clear. In this respect the Lias at Rødby is very reminiscent of the occurrences at the northern margin of the basin, Skagen and Frederikshavn.

In the Rhaetic at Ullerslev the quartz/feldspar ratio is mainly high, in contrast to all wells mentioned previously. A similar tendency can be observed in Rødby 1, although the values are more variable here. In the Lias at Rødby the values are, on the whole, lower.

In the non-opaque heavy-mineral assemblage the stable minerals are predominant in amount. It can be seen from the diagram, fig. 41, that in two thirds of the samples from these two wells tourmaline is present in greater amounts than zircon. This is yet another way in which these sections differ from the majority of those described previously. In Ullerslev 1 ca. 30% of the tourmaline grains are rounded or consist of subrounded grains with a well rounded core (see fig. 29). Staurolite and kyanite are found in considerable amounts with staurolite as the most prominent (fig. 40). Garnet is present but generally not in large amounts. In the Lias in Rødby 1 there are minor amounts of epidote and hornblende.

As indicated here these two wells differ from the previously mentioned wells in Jylland in several important respects concerning the composition of the clastic mineral assemblage.

Lavø 1 – Øresund (Plates XVI and XVII)

In the eastern occurrences the Øresund borings are particularly valuable in giving information about the nature of the material. This is especially true of the Lower Jurassic beds, whereas the data are more scattered and sporadic in the Middle and Upper Jurassic.

It can be seen that plant material is found almost everywhere in the Øresund section, in both the marine and non-marine deposits.

It should also be noted that glauconite is present in Lower Dogger and Kimmeridge deposits, but not in the Lias beds. In these main features there seems to be a good agreement with most of the borings referred to earlier.

The curve for the quartz/feldspar ratio has an extremely irregular course.

As to the non-opaque heavy-mineral fraction it should be noted first and foremost that epidote and hornblende are virtually absent. On the other hand garnet is found locally in substantial amounts, especially in the Middle Jurassic. In the Lower Jurassic beds, a connection can be traced between the feldspar content and the garnet content, as illustrated in the diagram, fig. 43; an analysis of Kågeröd arkose from Ottarp in Skåne is also given here (see appendix, p. 115). A comparable relation between the amount of feldspar and the amount of garnet cannot be shown for the Middle and Upper Jurassic beds. Staurolite and kyanite are only found in small amounts in the Lower Jurassic; staurolite is the more abundant of the two here. In the Middle, and especially the Upper, Jurassic these minerals become more abundant, and at the same time a change takes place in their relative amounts in favour of kyanite (see fig. 40). Taking the sequence as a whole, the stable minerals are the most prominent. As to the ratio between zircon and tourmaline, there are substantial variations throughout the section; there is a tendency for zircon to be dominant in the lower part

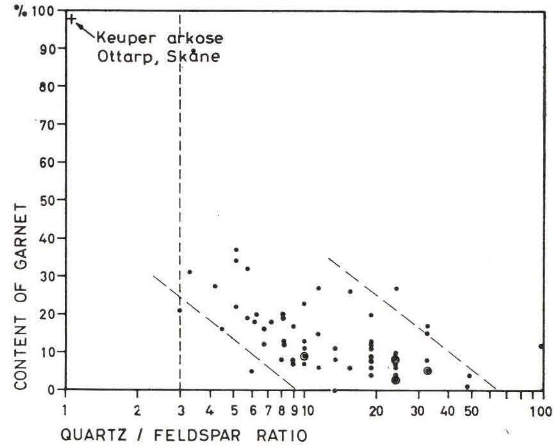


Fig. 43. Øresund; the relation between the garnet content and the quartz/feldspar ratio for the Lias sediments.

of the Lias, while tourmaline predominates in the Middle and Upper Lias as well as in the Upper Jurassic. If a comparison is made with the wells described previously, it can be seen that the Øresund occurrence differs from those in Jylland, but agrees fairly well with Rødby 1, in that the Lias has a rather high tourmaline content (see fig. 41).

There is only one analysis available from the Lias beds in Lavø 1, while there are six from the strata that have been referred to the Lower Cretaceous. It can be mentioned that the zircon/tourmaline ratio in the Lias deposits corresponds approximately to that found in the Lias in Øresund.

In connection with the Øresund occurrence reference can be made to a few analyses of the so-called glass sand from *Fyledalen* in Skåne. The glass sand is a presumed Middle Jurassic, obviously non-marine deposit, which may correspond to the strata in Øresund termed the Vilhelmsfält Formation. Analyses of six samples of the glass sand are given in the appendix (p. 115). It can be seen from these analyses that epidote and hornblende are totally absent and that in some samples there is a lot of garnet while others are garnet-free; it is also apparent that of the two minerals staurolite and kyanite, both of which are abundant, kyanite predominates, and finally that tourmaline exceeds zircon in amount. The glass sand from Fyledalen seems to correspond approximately in these characteristics to the Middle, and especially to the Upper, Jurassic beds in Øresund.

This treatment of the mineral distribution can be supplemented by an account of two analyses from *Bornholm*. According to Weyl and Werner (1952), the Lias beds at Hasle and at the mouth of the Stampeå have the following heavy mineral assemblage.

	Zircon	Rutile	Tourmaline	Titanite	Staurolite	Kyanite	Garnet	Epidote	Pyroxene
Hasle (siderite sandstone)	26	6	1	17	3	1	36	6	2
Mouth of the Stampeå...	15	5	5	7	1	5	22	40	–

The most remarkable feature must surely be the rather high content of epidote and titanite. This is one of the features showing that this material from Bornholm is quite different from the material in Øresund, but rather closely comparable with the far-off occurrences in north Jylland, especially Skagen. It must be emphasized however that it is as yet unknown whether these two analyses can be regarded as representative of the Jurassic of Bornholm.

Summary

In the figures 44–48 a survey of certain of the features of the heavy-mineral distribution discussed in the preceding pages has been attempted. A feature shown in these diagrams is the average heavy-mineral assemblage for each of the major chronostratigraphical units in the different borings. As was already pointed out, the study material is of very uneven quality; this is not only because there are considerably fewer samples from certain localities than from others, but also because the material from certain stratigraphical sections is finer-grained and thus less suitable for these investigations than material from other sections. The individual diagrams in fig. 44–48 are not therefore equally representative. An attempt has been made to indicate this by placing a figure beside each diagram to show how many heavy-mineral spectra the particular diagram is based on.

It seems possible to trace in these diagrams a certain regional differentiation in the distribution of the mineral assemblages.

Along the northern edge of the basin there is an epidote-rich assemblage; this becomes prominent to a varying extent throughout the whole of the depositional period under consideration. A comparable assemblage is evidently also found in the Lias in Bornholm, which presumably represents in the same way a position near the margin of the depositional area. In the Øresund occurrence, situated about midway between the localities in north Jylland and Bornholm, there is, however, no suggestion of such an epidote-rich assemblage.

In north Jylland an apparently gradual reduction can be traced in the proportion of epidote, from the edge of the basin out into the deeper, more central part of the depositional area. Here the Rhaetic deposits (Gassum Formation) are generally characterized by a high garnet content (Vedsted and Fjerritslev are exceptions) and by the fact that zircon is more abundant than tourmaline; in addition these deposits are very rich in feldspar. The deposits of the same age along the edge of the Ringkøbing-Fyn High (Ullerslev Formation) differ from those just mentioned in being poorer in feldspar and garnet and in containing considerably more tourmaline; furthermore, kyanite and especially staurolite play a larger role here. The two formations are thus distinctly different; each formation obviously comprises a separate heavy mineral province.

The main feature of the Lias beds (Fjerritslev Formation) appears to be that the heavy-mineral assemblage matches that in the underlying Rhaetic deposits. In the area of development of the Gassum Formation the Lias beds are likewise rather rich in garnet and zircon. The Lias at Rødby, where the substratum is formed by the Ullerslev Formation, resembles the last-named in having a rather low garnet content and a rather large content of tourmaline and staurolite. The mineral provinces established in the Rhaetic thus seem to be valid in more or less unaltered form in the Lias. There is also the Øresund-Lavø area. The Rhaetic mineral assemblage is not yet known in this area, but its Lower Jurassic heavy-mineral association does not seem to fit completely into any of the provinces mentioned earlier; this may be an independent, eastern province.

The Middle Jurassic Haldager Formation is, on the whole rather poor in feldspar; the garnet content is locally considerably lower than in the underlying deposits, while the stable minerals are more prominent. It should be noted that these features also apply to some extent inside the northern epidote province. The comparable deposits in the Øresund area (Vilhelmsfält Formation) are clearly different, in particular because they have a high garnet content, but also because staurolite and kyanite are somewhat more prominent.

The mineral content in the Upper Jurassic beds seems to agree more or less with that in the underlying deposits. The regional variation is, at any rate, about the same as before: a northern province characterized by epidote, a province situated to the south with a predominantly stable heavy-mineral assemblage and finally an eastern province (Øresund) characterized by a rather large tourmaline and kyanite content. In the Lower Cretaceous there is on the whole a similar distribution; knowledge of the eastern province is, however, very limited.

It thus appears that in the area studied it is possible to distinguish certain regions whose mineral assemblages do indeed vary upwards through the sequence, but whose individual characteristics are maintained in broad outline.

THE REASONS FOR THE MINERAL DISTRIBUTION

The mineral content of a sandy sediment is the result of the combined effects of many different factors; these can be classified under the following main headings.

1) The composition of the source material
2) The effects of weathering
3) The effects of transporting and depositional processes
4) The effects of diagenetic processes.

In the following section an attempt will be made to elucidate the significance of these different factors in the development of the mineral content of these particular sediments.

Diagenesis

The question that first arises is whether diagenesis, i.e. the sequence of processes after deposition, has substantially altered the original mineral assemblage. Even if special textural studies helped by thin-section investigations have, until now, only been undertaken to a limited extent, the general observations made on the nature and state of the minerals have furnished certain criteria for evaluating features showing diagenetic influence. It must be stated immediately that there is evidence of several different types of diagenesis, including both constructive and destructive diagenesis.

During the discussion of the various minerals and mineral groups it was mentioned that because of the grain form, and the nature of the grain surface, certain components must be regarded as authigenic. This applies to pyrite, siderite and barytes. As to pyrite, it was mentioned, with reference to LOVE (1964), that its formation probably took place under reducing conditions a short time after the deposition; this corresponds to the diagenetic stage that FAIRBRIDGE (1967) terms the syndiagenetic. Siderite has presumably been formed under almost the same conditions; ZIMMERLE (1963) states that this applies in the Dogger deposits in north Germany. Barytes, on the other hand, is usually considered to belong to a late diagenetic stage (ZIMMERLE, 1963; VON ENGELHARDT, 1967). The latter author mentions an example where the formation of barytes evidently did not take place during the subsidence of the strata, but during a later elevation of the beds to a higher level in the crust. It is stated that precipitation of barytes can occur where barium-containing, sulphate-free solutions coming from depth meet sulphate-containing pore water at a level fairly near surface. $BaSO_4$ can presumably form in both the diagenetic stages that in FAIRBRIDGE's (1967) terminology are named the anadiagenetic and the epidiagenetic. Amongst the other examples of diagenetic growth in these sediments can be mentioned quartz overgrowths on quartz grains, and also feldspar overgrowths, which were observed here and there on clastic feldspar grains. The coarse-grained calcite that constitutes the cement in the Upper Jurassic "limestone" bands can be mentioned here; the quartz grains enclosed in this calcite are nearly all characterized by authigenic growth (fig. 16). On the grounds of the textural relations, the calcite must be regarded as of later formation than the quartz, and it can presumably be inferred that the latest diagenetic stage here was characterized by a weakly basic environment (pH $\geqslant 7.8$).

As to the TiO_2-minerals, it is considered that important changes occurred after deposition. As mentioned during the description of the minerals, brookite, most of the anatase and presumably also a considerable part of the aggregate-polarized grains, as well as some of the idiomorphic rutile grains, have been formed authigenetically. It was also stated that there appears to be a smooth transition between non-opaque TiO_2-mineral aggregates on the one side and opaque grains that seem to be leucoxene on the other. According to current opinion leucoxene is an alteration product of ilmenite, and it is considered (see MILNER et al., 1962) that this alteration usually takes place in situ in the sediments after deposition, i.e. diagenetically. It is thus very likely that this is a series of TiO_2-minerals whose formation is controlled less by addition of new material than by local reorganization of existing material in the sediment (ilmenite → leucoxene → non-opaque TiO_2-mineral aggregates → coarser-grained minerals comprising brookite, anatase and possibly rutile). However, for the time being this is merely a conjecture whose verification must wait until ore-microscopic analysis and thin-section studies have thrown more light on, respectively, the nature of the opaque minerals and textural relations of the grains.

In addition to these examples where diagenesis has led to authigenic mineral formation, there are also clear examples in the material of destructive diagenesis or "interstratal solution". As mentioned previously, a number of minerals are characterized by superficial etching in the form of facets and pits; the minerals in question are: titanite, staurolite, kyanite, garnet and epidote. It might be thought that dissolution phenomena of this nature represent traces of weathering effects from the time preceding the formation of the sediments. This possibility seems, however, to be excluded in those cases where the etch marks are present on rounded surfaces, but even where the etched surfaces can not be seen to be affected by wear there may well have been a diagenetic influence, an influence so profound that the whole of the original grain surface has been removed. It is considered to be very probable indeed that destructive diagenesis has been active in these sediments. The question now is merely whether these dissolution processes can have been so extensive and profound that certain minerals in the mineral assemblage of the sediment as originally deposited have been completely removed in larger or smaller parts of the succession. The importance of this question in the evaluation of the reasons for such features as the southern limit of the northern epidote province is obvious.

In this connection it should be recalled that PETTIJOHN (1957) considers "interstratal solution" to be the reason that older geological formations in many cases are much poorer in certain minerals than younger deposits. WIESENEDER (1953) also deals with this question; certain of the main points of view from his work will be referred to briefly.

WIESENEDER makes a comparison between mineral stability under acid weathering conditions and the stability under diagenesis; the order of stability is indicated so that the least stable minerals are placed uppermost in the columns

Surface weathering	*Diagenesis*
(cf. WEYL, 1949, 1950, 1952)	(cf. PETTIJOHN, 1957)
Olivine	Olivine
Augite, apatite, hornblende	Augite, hornblende
Garnet	Epidote
Epidote[1])	Sillimanite, kyanite, andalusite, staurolite
Sillimanite	Apatite
Staurolite, kyanite, andalusite	Garnet
Tourmaline, zircon, rutile	Tourmaline, zircon, rutile

The remarkable thing about this classification is, in particular, that apatite and garnet, which are considered to be very susceptible to weathering, are apparently relatively stable under diagenetic conditions.

WIESENEDER states in addition that in deposits where weathering and diagenesis have not notably influenced the mineral content one of the following three heavy-mineral associations is usually encountered.

(1) A garnet-hornblende-epidote association with some content of staurolite and kyanite, originating from crystalline rock denudation areas of "alpine type".

(2) A garnet-hornblende association, which may contain augite and rather large amounts of zircon, but without epidote. This comes from areas of high-metamorphic crystalline rocks.

(3) A zircon association, with tourmaline, apatite, fresh biotite and possibly other accompanying minerals, originating from granite.

Under the influence of acid surface-weathering type (1) is stated to be altered to

(4) An epidote association with accompanying minerals that are stable under weathering, and with continued weathering to

(5) A staurolite association; it is mentioned that this last-named association is of a type not known from crystalline formations.

If, on the other hand, type (1) is subjected to diagenetic influence, the sequence of events should be as follows:

(6) A garnet-epidote-staurolite association should be formed first, and thereafter

(7) A garnet-staurolite association, and finally

(8) A garnet association.

As to type (3) it is stated that influence of weathering and diagenesis can best be traced in the content of feldspar, apatite and biotite. If the associations (1) and (2) are subjected to the combined effects of thorough weathering and extensive diagenesis the result should be

(9) A zircon-tourmaline-rutile association, with a certain resemblance to type (3), but differing from it in some respects, for instance in the weight per cent content of heavy minerals, which is rather low.

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[1]) According to WEYL (1952 b) epidote may in some cases be more unstable than garnet.

This account of WIESENEDER's results can be supplemented by a reference to G. LUDWIG (1960) who finds in the north German Wealden sediments that garnet is also stable under diagenesis, while staurolite, kyanite and epidote show varying degrees of instability, staurolite being the most stable and epidote the least stable. In addition it can be mentioned that VON ENGELHARDT (1967) considers diagenetic heavy-mineral dissolution and also feldspar kaolinization to take place where the environment is acid, while the dissolution ceases, or is greatly restricted in more basic surroundings.

If the results of the present investigations are seen against the background sketched in the preceding section, it might at first appear logical to explain a number of the earlier mentioned characteristics of the mineral assemblages as being the result of diagenetic dissolution. The following examples can be given. 1) The low hornblende content of the epidote province could be due to the hornblende having been removed diagenetically. 2) The disappearance of the epidote province southwards could be due to diagenesis having been more active in the deeper part of the basin and having removed in this area an original epidote content; in other words, the more stable province that succeeds the epidote province southwards could originally have been a part of that epidote province. 3) The changes in the abundance of, and ratio between, kyanite and staurolite that occur in the area could be diagenetically conditioned. 4) The variations in the abundance of garnet could be due to diagenesis having been more advanced and thorough in some places than in others.

In evaluating such facts, however, not only the abundance of the minerals but also their condition must be taken into account. If a mineral, for example epidote, is entirely absent in study material, it is not possible to say with certainty whether the particular mineral has never been in the material, or whether it really was present originally, but removed during later diagenesis. If the mineral occurs in small amount, there must be in the condition of the mineral grains (e.g. degree of etching) a basis for judging whether the grains represent a small dissolution remnant of an originally larger assemblage. On the basis of these considerations it will be attempted in the following section to elucidate the influence of destructive diagenesis on these particular sediments.

During the discussion of the minerals it was mentioned that hornblende is not characterized by signs of dissolution processes, since etch marks (e.g. jagged crystal ends) were nowhere observed with certainty; the examples of hornblende grains shown in fig. 36 are typical of the material. This is in a way remarkable, as hornblende was regarded in this discussion (p. 84) as being amongst the most unstable minerals. Because of the obviously unaffected state of the hornblende grains it is found reasonable to conclude that the relatively low hornblende content is probably an original feature of the sedimentary material and that it is not likely to be the outcome of diagenetic dissolution.

As to epidote, a fair number of grains are characterized by dissolution phenomena and some of these obviously to a considerable extent; this is especially true in Frederikshavn City 1. It must be regarded as unquestionable that diagenesis has been active here, and it cannot be excluded that certain of the variations in the amount of epidote found in the Frederikshavn City 1 well section could be attributable to diagenetic dissolution. As indicated previously, one of the main problems in this connection is whether the northern epidote province has extended farther south, but was reduced in area as a result of diagenetic breakdown of epidote in the deeper part of the basin. Several sections in the wells in Jylland contain no epidote at all; there is thus a possibility here, although hardly verifiable, that diagenesis may have removed an original epidote content. In the wells Flyvbjerg 1 and Børglum 1 there is an epidote content that is rather large in some places and in other places rather small. By far the majority of these grains are completely intact, i.e. without traces of etching, while a minority have corrosion marks, but obviously quite weak. In Haldager 1 there is a small content of epidote in the Lias, as well as in the deposits in the transition zone between the Jurassic and the Cretaceous, and in Gassum 1 a small number of epidote grains occur in the Rhaetic and the Malm. These grains are like those mentioned previously, either being completely without etch marks or bearing insignificant traces of dissolution. There do not therefore seem to be in these observations any grounds for considering that this is a version of the epidote province impoverished by diagenetic breakdown.

As mentioned, there are distinct signs that both kyanite and staurolite have been affected by diagenetic dissolution. In samples where both minerals appear together an inspection of the grains did not reveal any conspicuous difference in the amount of etching of the two minerals. This was true for example in Ullerslev 1 where etched grains are fairly common. In addition, it can be mentioned that in certain parts of the sequence where the total amount of the two minerals is relatively low and where staurolite predominates in amount over kyanite, the grains have been found to be either completely intact or only weakly etched; this is true, for instance, in Børglum 1 and Flyvbjerg 1, as well as in Haldager 1 (Malm – Lower Cretaceous) and Gassum 1 (Malm). It has not therefore been possible up till now to demonstrate that the variations in the amounts of the minerals and changes in their ratio that exist in the analytical material could be attributable to diagenesis.

As to garnet, the majority of the grains are either free of etch marks or only lightly etched on the surface. There are, however, exceptions, most notably in the Rhaetic in Vedsted 1. In this well all the garnet grains are strongly etched, so much so that nowhere was any trace of the original grain surface found; some of the grains have acquired bizarre forms as a result of the etching. As mentioned earlier, the Rhaetic at Vedsted is much poorer in garnet than the comparable beds in the other wells in Jylland. There are grounds here for considering that a substantial breakdown of the original mineral assemblage has taken place under the effects of diagenesis. In the Lower Cretaceous in Lavø 1 the garnet grains are also deeply etched.

It was mentioned previously, with reference to VON ENGELHARDT (1967), that a low pH in the percolating water seems to be a precondition for diagenetic mineral dissolution. It is therefore considered that this applied in the Rhaetic beds in Vedsted 1. In the localities where diagenesis has obviously been less aggressive towards the mineral content, the degree of acidity of the water has possibly been lower. There is, however, only a small amount of direct information about this. Chemical analyses of the formation water are only available from Haldager 1 (B. DINESEN, 1961); in the five samples examined from the Middle Jurassic Haldager Formation, the following values for pH were found: 7.50, 6.92, 7.12, 6.34, 6.82. The fact that these values lie not very far from the neutral point taken together with the fact that in these particular beds no obvious traces of destructive diagenesis were found seems to be in good agreement with the opinion expressed by VON ENGELHARDT.

This evaluation of the influence of diagenesis advanced in the preceding section can be briefly summarized as follows.

There is clear evidence in these sediments of the work of diagenesis, both in the form of authigenic mineral formation and in the form of dissolution of the clastic mineral grains. These dissolution processes have been very thorough locally, and presumably in such places the original clastic mineral assemblage has been radically changed. However, in the majority of the occurrences examined it seems that destructive diagenesis has either played no important part or has resulted only in a slight corrosion of the surfaces of the mineral grains. It is therefore considered reasonable for the time being to accept that the clastic mineral distribution found by analysis, with a few exceptions corresponds mainly to the mineral distribution of the sedimentary material as deposited.

The influence of the transporting and depositional processes

During transport of the material to the place of deposition abrasion of the grains and also sorting of grains according to size or mass undoubtedly occurred.

Rounding of grains is a result of wear during transport. In the material under consideration there are all transitions from very well rounded grains to grains in which rounding is not recognizable. This presumably reflects the fact that certain grains have been transported over greater distances than others. Long transport routes of this type can reasonably be regarded as having been divided up into several stages, or in other words, as representing several phases of redeposition.

It is well known from many sediments that there is a connection between grain size and mineral content. For example, the heavy-mineral distribution in the fine-grained fractions is different from that in the coarse-grained, in exactly the same material. The phenomena is usually called "granular variation"; it has been described in detail by VAN ANDEL (1950), and is also discussed by LARSEN and DINESEN (1959). The origin of this granular variation can be sought in two features, one the fact that in the parent rock there is a difference in the size of the various minerals, and the other the fact that during the processes of sedimentation there occurs a sorting of the minerals according to size or mass (size × density); it must be added, however, that any difference in the resistance of the components to weathering and abrasion can also have an effect. The granular variation has not been studied specially during these investigations, but certain features of the mineral distribution found may perhaps reflect this penomenon. As an example the Upper Jurassic deposits in Gassum 1 can be mentioned; a feature that can be seen in these deposits is that the coarsest-grained beds are very rich in zircon and poor in tourmaline, while the situation is reversed in the finer-grained beds. Another example is the Middle Jurassic in the borings Skagen 2 and Frederikshavn City 1. As stated earlier there is a good petrographical correlation between the wells for these beds in particular, namely in the course of the curves for the quartz/feldspar ratio and the garnet content; there is, however, also the difference that the beds at Frederikshavn are considerably richer in zircon than the beds at Skagen. This difference can perhaps be explained by granular variation, since the deposit is generally much coarser-grained at Frederikshavn than at Skagen. As indicated, certain variations in the composition of the mineral assemblages can probably be attributed to sorting of the material during the processes of sedimentation. This phenomenon cannot, on the other hand, explain the main features of the mineral distribution in the study area as a whole, since sediments of the same age and with the same grain size in the different "provinces" often have different mineral assemblages.

The main feature emerging from these considerations is therefore that if certain local occurrences are excepted neither the process of deposition nor the diagenetic mineral dissolution can be regarded as being of fundamental importance in the distribution into "provinces" indicated by the analytical results. The explanation must therefore presumably be sought in different sources for the material, and perhaps different transport routes. In order to explain these features it is necessary to consider the mineral content in relation to the lithostratigraphical formations referred to previously.

In the Rhaetic, sand-dominated deposits, two formations, the Ullerslev Formation and the Gassum Formation were established; both are regarded as deltaic deposits built outwards from the margin of the island extending from mid-Jylland (Ringkøbing) to Fyn (Sorgenfrei, 1963) and from the northern margin of the basin against Fennoscandia, respectively. The distinct difference in the mineral content of the two formations can thus be explained naturally as being due to supply of material from two different areas, which were evidently of mutually different composition. The "Gassum delta" is clearly the larger of the two, a feature that fits very well with the idea that in the larger, northern land area there was "room" for a much larger drainage area for the river system or river systems forming the background for delta formation than was the case with the "Ringkøbing-Fyn island". Certain of the variations in the mineral assemblage that are encountered in the Gassum Formation should perhaps be seen in this context as well; the fact that epidote occurs particularly in the northernmost part of the area springs especially to mind. This feature could be explained by assuming that the large delta was not built up from the north, but over a broader front from the north-east by several river systems containing material of somewhat varying composition. This attempt at an explanation is, however, hypothetical for the time being, partly because there are still no observation points in Kattegat.

In most of the area, the Lias is developed as the marine, clayey Fjerritslev Formation. It was found that the mineral content of this formation is essentially the same as that found in the underlying Rhaetic beds in the individual areas; i.e. it can be assumed that the supply routes for material that were established in the Rhaetic were essentially retained in the Lias, even if the depositional environment was another. For the Lias beds there are also observations from the more southern part of the Fennoscandian Border Zone (Øresund, Bornholm). If the geographical situation and the mineral content of the deposits are both taken into account, they lead to the idea that the deposits here were not brought from the same area and thus not by the same route as the deposits farther to the north-west in the basin. For a part of these deposits, the Hälsingborg beds, TROEDSSON (1951, pp. 126–132) has proposed the theory that they were formed in the estuarine area of a rather large river system ("Baltic river") which, with a flow towards the north-west, drained an area perhaps corresponding to the present Baltic. This question could not be elucidated further during the present investigations. One other idea can be mentioned, the idea that there might have been throughout the Danish Embayment and its continuation in the Polish Basin a considerable amount of material transport along the length of the basin from south-east towards north-west, for example, corresponding to the principle that seems to apply to the present-day Adriatic Sea; the predominant contribution of material here obviously comes from the River Po, which has its outlet at the "end" of the depositional area, whereas the contributions from the sides seems to be small by comparison. This "model" can scarcely be accepted for the Danish Embayment; for one thing, the derivation of the Rhaetic-Lias sediments in Jylland from the northern or north-eastern border zone of the basin can hardly be disputed. The same applies to the relation between the deposits in Fyn and Lolland, and the "Ringkøbing-Fyn island". The "model" does not seem to fit the Øresund and Bornholm occurrences well either, since the mineral assemblages in the two areas are too different from each other to enable a common south-east origin for both to be accepted as a matter of course. It must be emphasized, however, that as long as the heavy-mineral content in the Polish Rhaetic and Jurassic sediments is not known, this question can not be fully evaluated.

It seems reasonable for the time being, however, to keep to the view that the material as a whole has been brought in from the sides of the basin. Most of it was undoubtedly brought from Fennoscandia; there was presumably supply of material from several rivers, which reached the coast at several places.

The concept sketched here will be illustrated by referring to a present-day coastal area, the French Atlantic coast. The stretch from Brittany to a little south of the mouth of the Gironde corresponds approximately to the distance from Skagen to Bornholm; this example is thus of the same order of magnitude as the area being studied. A rather detailed petrographical analysis of the sediments of the coastal zone of the French Atlantic coast is available (DEBYSER, VATAN and BOYER, 1955). It emerges from this that there are three heavy mineral provinces along this stretch of coast. Farthest north is a Brittany province, whose characteristic minerals are staurolite and stable minerals. At the Loire estuary this is replaced by a Loire province, which has augite as a type mineral. This province extends southwards to the Gironde estuary, where it is replaced by a Gironde province, which is especially characterized by its content of fibrolite and andalusite. The assemblages in the Loire and Gironde provinces have clearly originated through the supply of fluviatile material brought in by the Rivers Loire and Gironde respectively; the position of each province on the south side of the particular river estuary associated with it is clearly a consequence of southward drift of material caused by waves and coastal currents. This example is intended to illustrate first and foremost the fact that it is by no means unrealistic to imagine that in the stretch from Skagen to Bornholm there may have been outlets for several larger or smaller river systems. The example has however only limited value in relation to the present problem since it only deals with the mineral distribution in the coastal zone itself, and not in the adjacent basin (Bay of Biscay); a less sharp delimination of the provinces must presumably be expected in the basin. The fact that there can be considerable differences in the position of the boundary line between two mineral provinces in the coastal zone and the basin respectively is, for example, known from the recent San Diego Trough out from the coast of California (SHEPARD and EINSELE, 1962); the explanation for this must be sought in the local hydrographical conditions. Reference can be made to yet another example, the present-day North Sea, where BAAK (1936) has examined the mineral distribution in the bottom sediments. One of the features to emerge from this work has been that in the southern part of the North Sea several heavy-mineral provinces can be distinguished; the distribution of one of these provinces, the H-province, seems to be determined by water movements in the area out from the Rhine estuary (see also DE GROOT, 1964, fig. 2).

The recent examples mentioned here should help to illustrate the concept that the main features in the mineral distribution in the Rhaetic-Lias deposits may well have been determined by varying supply routes for the material.

In the rest of the succession the province distribution seems, as mentioned earlier, to have remained more or less the same, although the composition of the provinces undergoes certain changes up through the sequence. The explanation may perhaps be that the transport routes for the material were basically the same, while the material brought in changed in composition in the course of time.

The influence of weathering processes

During the discussion of diagenesis it was also mentioned how the degree of resistance to weathering is considered to be different for the various minerals (p. 84).

The weathering that was operative in the denudation area can have had the result that certain unstable minerals were totally destroyed while others were attacked more superficially. Nothing is known about the first group, as the minerals belonging to it will not appear in the deposits, and wear during transport of minerals in the second group may possibly have removed the damaged surface layers completely. It is really very little that can be concluded about the significance of weathering in the composition of the mineral assemblages. So much is clear, however, that chemical weathering can hardly have been especially intense in sediments whose content of minerals susceptible to weathering (e.g. feldspar, garnet, epidote) is large. It seems, for instance, that this must apply to the Rhaetic-Lias in Jylland. On the other hand, the overlying Middle Jurassic deposits have quite another character since over large areas, a substantial part of the sequence has a rather low feldspar content, and at the same time a rather high content of stable heavy minerals.

This may indicate that the material in these deposits has undergone a more intense chemical weathering than the material in the older strata. It is undoubtedly possible to produce several different explanations for the change that takes place at the transition from Rhaetic-Lias to Dogger. One of these explanations will be given in the following section.

As mentioned previously, the Rhaetic Gassum Formation is considered to be a deltaic deposit built out from the north or north-east through supply of material from a fairly large river system. In the Lias a marine transgression took place so that the Rhaetic delta was flooded; the fact that in the Lias essentially the same type of material was supplied to the basin as during the Rhaetic suggests that the river system that built up the Rhaetic delta was also responsible for the supply of material in the Lias. The rise in sea level must however be presumed to have brought about an alteration in the conditions, for example in the erosional base-level in this river system; this presumably had the result that considerable amounts of material were deposited in the river bed, and possibly also that a delta-building took place at the outlet of the river system in the Lias sea. It is true that this hypotheses can not yet be checked, but it is considered to be quite reasonable; it is only necessary in this connection to refer to the Rhône delta where there is evidence of a change in the position of the delta caused by alterations in sea level during Quaternary time (LAGAAIJ and KOPSTEIN, 1964). In the Middle Jurassic a regression of the sea took place;

this may, of course, have had the result that the erosional base-level for the river course mentioned was lowered so that the presumed Lias river bed and deltaic sediments took on the character of terrace beds on each side of the river course. It is commonly accepted that during percolation of water through sandy river terraces, which are often very porous, an intense chemical weathering of the material can occur. This can be illustrated with the comment that VAN ANDEL (1952), who is not inclined to attribute great importance to weathering processes in heavy-mineral distribution in general, supports the concept that considerable heavy-mineral weathering can occur in terraces in particular. During river erosion of weathered terrace material of this type, the new river-transported deposits will receive an important supplement of more "mature" sedimentary material, a feature that, as was stated, seems to characterize an important part of the Middle Jurassic delta (Haldager Formation). The explanation given in outline here of the reasons that lie behind the alteration in the composition of the material at the transition between Lower and Middle Jurassic in the area in Jylland is, it must be stressed, a hypothesis that can scarcely be verified since the events referred to took place essentially outside the area that is recognized today as the Jurassic depositional area.

After the Dogger a rise in sea level occurred once more, so that marine Upper Jurassic deposits overlie the "Haldager delta", and after this, at the transition between the Jurassic and the Cretaceous, another regression took place. That is to say, the course of events during the Upper Jurassic and the beginning of Lower Cretaceous times can be presumed to have corresponded closely to that sketched for the Lias and Dogger. It is therefore considered logical, following the reasoning applied to the Dogger beds, to explain the zone that occurs in the Lower Cretaceous Skagen Formation ("Skagen delta"), a zone with rather low feldspar content and a comparable low content of unstable minerals (especially epidote), as being the result of these events.

It thus appears that weathering effects in interplay with alterations in sea level can have been an important factor in causing certain of the major changes occurring through the sequence in the composition of the mineral assemblage.

The foregoing considerations have been aimed at the occurrences in Jylland since there is in this area rather good observation material to start off with. In the remaining areas there is only scattered information about the conditions in the part of the sequence that is younger than the Lias; no basis has therefore been found up till now for deciding whether the "model" mentioned previously can also be applied to these areas.

Finally it can be mentioned that the breakdown due to weathering, which seems to have affected certain glauconite grains (see p. 44), must presumably be taken as indicating that an in situ weathering also took place locally in the depositional area; glauconite grains affected by weathering in this manner have been found in the Malm in Skagen 2, as well as in the Dogger and Lower Cretaceous (the uppermost part – sample no. 175) in Frederikshavn City 1.

Another piece of evidence showing in situ weathering is found in the form of a variegated horizon at the top of the Lias in Rødby 1 (see p. 33); a second variegated horizon appears in the Upper Jurassic in Gassum 1 (see p. 36). It should be said about the variegated beds in the Pankarp Formation (Lias beta) in Øresund that they are not regarded as representing an in situ weathering; this opinion is based on BÖLAU's (1954) analysis and discussion of comparable beds in Skåne.

The composition of the source material

It could be assumed beforehand that in a depositional complex such as this, comprising such a large area and representing such a long period of time, material of differing origins must be involved. As indicated previously, this appears to be true of this area.

On consideration of the components it is found likely that certain of them must be derived from older sedimentary formations. The components in question are well rounded grains of minerals that are stable under weathering and resistant to wear, e.g. quartz, zircon, rutile and tourmaline, but also less intensely worn grains of quartz and tourmaline that contain a more or less rounded core (see pp. 50, 57) must be considered to have this origin. However, certain reservations must be made when considering zircon, which, as mentioned on p. 55, is not regarded as recrystallizing under metamorphism; i.e. rounded zircon grains may stem both from older sedimentary formations and from metamorphic complexes of sedimentary origin. Other minerals such as pyroxene, hornblende, epidote, garnet and feldspar, which are regarded as being among the minerals susceptible to weathering, can hardly, on the other hand, have gone through several sedimentary cycles and can presumably be referred to crystalline source rocks. On the basis of these rather generalized assumptions and taking account of the relative amounts of the components, an attempt will be made in the following section to throw light on the source material for the sediments of the various areas.

The epidote-rich province in the northernmost part of the depositional area can probably be regarded as having its origins essentially in a metamorphic complex situated in Fennoscandia. Since epidote is connected with the northernmost part of the depositional area, and since its area of development seems on the whole to be original, i.e. not controlled by diagenesis to any significant extent (see p. 86), it is considered reasonable to assume that the metamorphic complex was situated in the northern part of the drainage area for the river system or systems that brought material to the depositional area in north Jylland; just where this was is hard to say. To what extent the mineral spectra found in the deposits directly reflect the composition of the area of denudation is unknown. The possibility is present that an originally higher content of hornblende has been largely removed by weathering in the denudation area (see WIESENEDER's types 1 and 2, referred to earlier on p. 84). This is however only a surmise. On the basis of the abundant presence of epidote it is believed that the metamorphic complex was a gneiss area metamorphosed in epidote-amphibolite facies. Tourmaline grains of the two-generation type appear here and there together with epidote; this is interpreted to mean that the denudation area for the deposits in north Jylland did not consist exclusively of metamorphic rocks, but also included sedimentary deposits. Amongst other minerals in the sediments there is also a characteristic content of kyanite and staurolite. To what extent these belong together with epidote from the point of view of origin is unknown; as an example of how the relation could perhaps be, it can be mentioned that there are in the gneiss of south-west Sweden bands of the so-called Horrsjöberg quartzite, which is stated to be rich in kyanite (P. GEIJER, 1963, p. 107).

The assemblage that is rather rich in garnet and feldspar, which characterizes the Rhaetic-Lias deposits within the area of development of the Gassum Formation and farthest to the north overlaps, and becomes mixed with the epidote assemblage, can likewise be considered to be derived from a metamorphic denudation area. On the basis of evidence from the area of sedimentation it is estimated that this metamorphic complex was situated farther to the south than the complex referred to previously. It can be mentioned, as a help in elucidating the position of this denudation area, that this particular mineral assemblage is not only characteristic of the Rhaetic-Lias deposits, but also for parts of the underlying Keuper beds, which include rather coarse-grained arkoses. Even if these, in line with the comparable beds in Skåne (Kågeröd Formation), can be regarded as fanglomerates transported by mud streams (TROEDSSON, 1942), it is not likely that they are the result of long-distance transport in the real sense. It is therefore highly likely that this area of denudation was situated in an immediately adjacent part of Fennoscandia. In addition to the high content of garnet and feldspar there is in places a very high titanite content in these sediments, but, on the other hand, only exceptionally, hornblende, and then only in rather small amount. It is especially likely that an originally high content of hornblende has been largely removed by weathering, but it must however be emphasized that apart from this no evidence was found to suggest that weathering processes had any significant effect. It can be judged, alone on the basis of the high garnet content of the associations, that this particular crystalline complex was characterized by a higher grade of metamorphism than the complex mentioned earlier. The denudation area for these deposits must likewise be assumed to have included minor occurrences of older sediments, since, for example, the two-generation tourmaline grains described earlier appear here and there in the deposits.

It must therefore be assumed that the "immature" mineral associations that are so obviously present in parts of the depositional area in Jylland are derived essentially from basement areas in Fennoscandia. The zones with more "mature" associations, which appear especially in the Dogger and the basal part of the

Lower Cretaceous, can, with reference to the preceding section (p. 92), be considered to have almost the same origin as the "immature" associations but to have been changed by having undergone through a more thorough process of weathering and redeposition, determined by alterations in sea level.

In contrast, the mineral assemblage of the Rhaetic-Lias sediments within the area of development of the Ullerslev Formation must probably be considered to have arisen mainly by reworking of older sediments. The composition of the mineral assemblage, as well as the fact that a very considerable number of the tourmaline grains either are perfectly rounded or consist of the two-generation type, indicates this. The source materials for these sediments can, on the basis of the geographical position of the sediments be assumed to have been localized in the Ringkøbing-Fyn High. This is built up of a basement foundation overlain by a sedimentary cover consisting partly of Triassic beds and partly of older sandstone deposits, which for the time being are referred to the Permian or the Eocambrian (the boring Ringe 1, see SORGENFREI and BUCH, 1964). These older beds have not yet been examined for their heavy mineral content; the question whether the Rhaetic-Lias sediments can have been derived from material such as this therefore remains open for the time being.

Very little is known about the mineral content of the Rhaetic Vinding Formation; however, as mentioned elsewhere (p. 76), the occurrence of titanite seems to point to a correlation with the Rhaetic beds in the boring Harte 2, situated on the flank of the Ringkøbing-Fyn High. It is therefore possible that the source material for these beds was also situated in this structural high. It should be noted that, according to NOE-NYGAARD (1963), titanite is found as an accessory mineral in the basement in the boring Grindsted 1.

The Lias beds in the Øresund area are characterized essentially by stable mineral associations, which at first glance might seem to be derived from older sediments. It is however possible that a more complicated origin is involved. In certain parts of the sequence there is a higher content of garnet than in others. Where the garnet content is relatively large, there is usually a rather large feldspar content (see fig. 43); these components thus seem to belong together. It can also be seen in fig. 43 that almost the same correlation between these two components can be traced in an analysis of the Upper Triassic Kågeröd Formation at Ottarp in Skåne; the values here are just much greater. On the assumption that this analysis is representative of the Kågeröd Formation in this area, the diagram (fig. 43) can be interpreted to mean that the Lias sediments consist of a mixture of a local garnet-rich and feldspar-rich Kågeröd association and a second, stable mineral association, possibly stemming from more mature sedimentary source material. This is, of course, a very weakly supported hypothesis; for one thing, so little is as yet known about the heavy mineral content of the Kågeröd Formation. That this theory is nevertheless produced, is due mainly to the fact that it seems to agree more or less with the opinion that Troedsson (1951, p. 129–132) has expressed, that, judging by their lithology, the Rhaetic-Lias deposits of the area consist partly of locally derived material (from Archaean rocks or the Kågeröd arkoses) deposited along the edge of the basin in Skåne and partly of material that has been transported farther, possibly brought from the south-east. In this connection it can also be mentioned that Hagermann and Borell (1954), by means of special granulometric studies, have discovered that several occurrences of Lias alpha sandstone in Skåne are made up of two different types of grain. All in all, there seems to be some basis for the theory that these Lias deposits consist of material of different origins; the major part, the stable association, was possibly brought from the east or south-east by a river system (see Troedsson's (1951, p. 132) "Baltic river"), whose drainage area may have comprised a part of Fennoscandia that was at that time covered by sediments; this can, however, only be a hypothesis for the time being. In the Middle and Upper Jurassic, mineral assemblages appear that are different from those in the Lower Jurassic. The denudation area must therefore have had a different composition, but there is nothing to indicate with certainty that it had altered character from sedimentary to metamorphic.

In contrast with this, the epidote assemblage in the Jurassic beds of Bornholm can be regarded as coming from a metamorphic area; based on knowledge of the basement in Bornholm (see Micheelsen, 1961; Noe-Nygaard, 1963) it is concluded that the metamorphic denudation area that supplied this material probably lay outside the present-day Bornholm. In this connection it can also be recalled that Graff-Petersen (1961, p. 115) considers that the source area for the Jurassic clay of Bornholm may lie outside Bornholm. For the sake of completion it can be added that the occurrence of mud-stream sediments (Gry, 1960) can be taken as indicating that the Jurassic deposits of Bornholm also contain material of local origin.

Summary

In the preceding section observations were made about the various factors that may have influenced the development of the mineral assemblages of the Rhaetic – Jurassic – Lower Cretaceous sediments. The main features emerging from these considerations may be briefly outlined as follows:

1) The main features in the mineral distribution from area to area within the basin are considered to be connected with the fact that the material was brought in from various denudation areas. It seems that the supply routes had a rather permanent character during much of the depositional period. Fennoscandia obviously contributed the majority of the material, but a supplement was provided by the Ringkøbing-Fyn High. Metamorphic complexes and also older sedimentary formations were involved in these denudation areas.
2) Certain marked variations in the mineral distribution within the depositional

area in north Jylland are believed to indicate periods of more intense weathering and subsequent redeposition of material, determined by alterations in the palaeogeography of the area.

3) Certain local variations in the mineral distribution can be explained as granular variation determined by the depositional processes.
4) Diagenesis has left its mark, partly in the form of authigenic mineral formation, and partly in the form of corrosion of clastic mineral grains. It is thought that destructive diagenesis has only changed the original mineral assemblage in a few special cases.

THE BASIN AND THE DEVELOPMENT OF SEDIMENTATION

During the consideration of the lithology and mineral content of these sediments in the preceding chapters, several aspects of the genesis of the sediments were referred to. In the following section an attempt will be made to combine the various aspects in an account of the development of the sedimentation in the Danish Embayment in Rhaetic, Jurassic and Lower Cretaceous times.

As an aid to this representation the palaeogeographical maps shown in figs. 44–48 have been prepared. They are to some extent based on SORGENFREI's (1963) lithofacies maps, but have however in contrast with those the character of palaeographical maps of a more traditional type; it has been attempted particularly to demarcate on these maps the areas of deltaic deposition and those of marine deposition. The maps are thus neither a copy of, nor a substitute for, but rather a supplement to, SORGENFREI's maps. In the demarcation of the areas of deposition SORGENFREI's presentation has generally been followed; exceptions are, however, to be found in the maps for the Middle and Upper Jurassic and to a smaller extent the Lower Cretaceous, where the new results of the Øresund borings (LARSEN et al., 1965) have been used as a basis for indicating the extent of the deposits in the south-east part of the basin. It must be emphasized that there does of course exist considerable uncertainty in the drawing of the boundaries for the extent of the basin and also for the extent of the various facies because the observation points are few in relation to the size of the area; furthermore, the observation points are not uniformly distributed throughout the area. Diagrams showing the heavy-mineral distribution are drawn on the maps; each diagram indicates, as mentioned earlier (p. 80), the average composition for the analyses that are available from the particular boring. It is clear that it is only where there is a representative series of analyses from the particular deposits (see Plates II–XVII) that these diagrams can be considered to be representative. As indicated, the picture given by these maps of both the palaeogeography and the heavy mineral distribution should be regarded with caution.

THE BASIN AND THE SURROUNDINGS

The Danish Embayment is, as already mentioned, simply a subsidiary part of the north European depositional basin, which after late Palaeozoic times has occupied the area between, broadly speaking, Fennoscandia in the north and the remains of the Variscan mountain chain in the south. This north European depositional area, whose main extension is obviously east-west (see GIGNOUX, 1955), seems to have been one uninterrupted basin of sedimentation at certain periods, for instance in the Trias (see WURSTER, 1964b), while at other times it has obviously been divided up into a number of smaller separate basins, for example, during the period of transition from the Jurassic to the Cretaceous (MARTIN and WEILER, 1963; OERTLI et al., 1961); but also in periods when sedimentation was taking place over the larger part of the basin there were local areas with specially intense sedimentary accumulation, a fact that is brought out by maps showing bed thickness (BENTZ, 1958; RICHTER-BERNBURG and SCHOTT, 1959). These features are interpreted to mean that the north European depositional basin in the structural sense consists of a number of more or less local areas of uplift and subsidence. KÖLBEL (1957) has touched on these questions and shown on a map that the main trend of many of these structures is approximately NW–SE (see also POŻARYSKI, 1957), i.e. the same trend that is found in the Danish Embayment. It thus seems that the Danish Embayment fits naturally into the structural pattern that can be traced in the adjacent parts of the north European depositional basin.

On the basis of sedimentological considerations in general, it must be assumed that the denudation areas belonging to this north European depositional basin were first and foremost Fennoscandia and the Variscan mountains, in other words, that the supply of material took place predominantly from these areas. That this assumption is reasonable emerges from various investigations. First and foremost in this connection can be mentioned WURSTER's (1964b) opinion that in the pre-Rhaetic Keuper a large-scale transport of material took place from Fennosarmatia in a south-west direction through a ramifying river and delta system, which evidently flowed into the Tethys sea at a place where the present-day Western Alps are situated; it seems that certain details in the branching of this delta system were controlled by local structural conditions, but when the main direction of transport is considered, it does not seem possible to trace any marked influence from the previously mentioned NW–SE structures. The most important preconditions for this development were surely that the "North Continent" was a dominating palaeogeographical element and also that the climatic conditions were moist in parts of this land area so that rivers could arise here.

In the succeeding geological period also, the Rhaetic, Jurassic and Lower Cretaceous, materials of northern origin seem to be traceable quite far to the south in the basin. In the Middle Rhaetic sandstone formations in the Lower Saxony Basin (SCHOTT, 1942), VON ENGELHARDT (1942) has found that certain mineral assemblages have evidently been brought from the Harz and the Flechtinger Mountains, whereas other assemblages, containing for example reddish and colourless garnet are presumably of a more northern origin. Roughly the same state of affairs is found in both the Jurassic and the Lower Cretaceous (DEECKE, 1935; BRINKMANN, 1937; see also, HOFFMANN, 1949; KUMM, 1952). DEECKE operates with several different denudation areas, including a northern area, which is given the neutral designation "the continent north of the River Aller". According to BRINKMANN this must be considered to be Fennoscandia. The mineral assemblages that are referred to it are garnet-bearing and sometimes hornblende- and epidote-bearing; it may be stated here that according to WEYL (1949), epidote was mistakenly recorded as diopside by DEECKE (1935). It is especially in the Middle Jurassic (Cornbrash sandstone) that the epidote assemblage is found far to the south, but epidote-bearing material also appears in the Lower Cretaceous at Ahrensburg and other places in north Germany (DEECKE, 1935; LUDWIG, 1960). In localizing the place of origin of these mineral assemblages there are several possibilities. For example, it could well be that the Ringkøbing-Fyn High was the denudation area, but there is still no verification of this. If, as BRINKMANN believes, it really was Fennoscandia that the material came from, it seems most logical to assume that the southern part of Fennoscandia was the part in question. This would fit very well with the fact that in the Jurassic of Bornholm a somewhat similar epidote assemblage to that in north Germany is apparently encountered. The question of origin must for the time being remain as not finally cleared up, but it seems to emerge from the facts that have been advanced that transport of material from the north or north-east was a characteristic feature of the northern Europe of that period. In the Danish Embayment it is precisely transport from the north or north-east that is presumed to have been predominant (see p. 89–90).

THE STRUCTURE OF THE DANISH EMBAYMENT

It was mentioned in the preceding section that, in accordance with its elongation from north-west to south-east, the Danish Embayment can be regarded as being part of the structural system that characterizes the underground, particularly in north Germany and Poland.

Within the Danish Embayment it is clear that the accumulation of sediment was not uniform throughout. It can be seen on the cross sections in fig. 3 (p. 22) that the greatest thickness of sediment is found at Fjerritslev, at a distance of over 100 km from the margin of the basin, and that there is obviously a steady increase in thickness from the border zone out to this place in the basin. To what extent even greater thicknesses of beds occur to the south-west, i.e. in the salt dome area, is unknown at present but southwards from the area at Fjerritslev (line B. fig. 3) the thickness of beds is again decreasing. In the eastern part of the basin (line C. fig. 3) the greatest thickness is obviously found in the Øresund area, where the distance from the margin of the basin can be presumed to have been quite short since the sediments, including some of the marine beds, are relatively coarse-grained. Reference can also be made here to Bornholm, where the Jurassic beds are also very thick and have evidently been formed in a marginal part of the basin; GRY (1951, 1960) has shown that in this marginal zone a granite horst was exposed to erosion during the deposition. The three areas mentioned here fall on a line trending about NW–SE. It is presumed that this line represents a tectonically built zone of subsidence, which was active during the major part of the Jurassic period. It should be noted that this zone does not follow, but forms an acute angle with, the long axis of the basin, and furthermore that in the stretch from Øresund to Bornholm it coincides at least in part with the Fennoscandian Border Zone, which nowadays appears as the structural high limiting the Danish Embayment to the north-east (see fig. 1, p. 10). The zone can be seen to stand out on the palaeogeographical maps since it is not noticeably influenced as an area of sedimentation by the emergence that obviously affected the southern part of the Danish Embayment during the Middle and Upper Jurassic.

In the Lower Cretaceous the circumstances appear to be different in that the Øresund area and the area immediately to the south-east obviously no longer appear as a zone of sedimentation in the same way as earlier. This may perhaps be connected with the fact that there were tectonic movements and that these may have taken place during the period of transition from the Jurassic to the Cretaceous. In this connection it may be mentioned that during the investigation of the Øresund borings (LARSEN et al., 1965; LARSEN, 1966) it was clearly shown 1) that the entire Jurassic sequence, whose youngest part here is the Kimmeridgian (Fyledal clay), is deformed, 2) that this deformation has the character of a large, NW–SE trending flexure, which dips steeply (ca. 45°) to the south-west under the Cretaceous beds, 3) that the flexure is overlain with angular unconformity by the Upper Cretaceous Campanian-Santonian sandstone (Lunda sandstone), and 4) that these Cretaceous deposits are also somewhat deformed in the area near the boundary with the flexure. It is concluded from this that the formation of the flexure, i.e. the elevation of the area on the north-east side in relation to the area on the south-west side, took place after the Kimmeridgian and before Campanian-Santonian times, and that there were also later movements in the flexure. With reference to HADDING (1933) and K. HANSEN (1939) it can be taken that comparable and probably simultaneous tectonic deformation took place farther to the south-east, in Skåne, and also in Bornholm. With these events the Fennoscandian Border Zone in the form it is known in today must presumably have been formed in broad outline; this should thus have happened mainly in the period between the Kimmeridgian and the Campanian-Santonian, but it must be added that further development of the structure by means of tectonic movements occurred later. The possibility mentioned earlier that the structural changes may have taken place in the period of transition from the Jurassic to the Cretaceous, can only at present be a suggestion, based mainly on the fact that Lower Cretaceous deposits have not been encountered in the Øresund borings or in that part of Skåne that lies nearest to the south-east (LARSEN et al., 1965), but on the other hand are found in the part of the basin in Sjælland (e.g. Lavø 1) that obviously did not function as a sedimentation area in the Middle and Upper Jurassic. This could suggest that a subsidence of this area occurred in the Lower Cretaceous; such a feature could well be connected with flexure formation.

It emerges from what has been said that certain major features in the development of the area of sedimentation can be seen as the result of tectonic events, but also smaller, more local structural changes seem to have occurred at certain places in the basin. Reference will be made first to the wells Fjerritslev 1 and 2. These are in mutual agreement in their stratigraphical subdivision and in the lithology of the sequence, but there is a very great difference in thickness of beds between the wells (see fig. 3, p. 22). When the change in thickness of beds that occurs from the margin of the basin in the north out to this area in the basin is considered, it must be assumed that the great thickness in Fjerritslev 2 is the "normal" for the area, while the small thickness in well 1 must be regarded as special. The explanation of the thickness in Fjerritslev 1 is presumably that this well is situated on a local structural high, which has had an influence during the whole of the Jurassic and the Lower Cretaceous. When it is considered that the structure seems to be of a local nature (SORGENFREI and BUCH, 1964), and that the area lies on the edge of a salt dome province, it seems reasonable to conclude that there is here a reflection of salt-tectonic movements of Jurassic and Lower Cretaceous age. Another example, where salt-tectonic influence seems indisputable, is Uglev 1. In this well the Middle Jurassic rests directly on the cap rock of a salt dome. The fact that in this area, which was obviously far from the coast, both Rhaetic and Lias are absent, must be regarded as the result of the presence of the salt dome. On the other hand, it is still unsettled whether the Rhaetic and the Lias were originally present, but removed by erosion caused by the upward rise of the salt dome, or whether such beds were not deposited because the dome already existed at that time. Finally, reference will be made to Gassum 1. This boring lies in the central part of the basin, and the development of sedimentation that took place here up till, and during, the Lias seems to agree very well with its position. It may therefore seem surprising at first glance that the Middle Jurassic is absent, and that there is, in the lower part of the Upper Jurassic a variegated horizon, presumably affected by weathering. SORGENFREI (1963) has interpreted this in his lithofacies map covering the Middle Jurassic to mean that the Gassum area during this period lay completely outside the area of deposition. Seen from certain angles this is also quite conceivable, but if what was mentioned in the preceding section is accepted, namely, that a tectonically determined zone of subsidence ran along the length of the basin from the Fjerritslev area over Øresund to Bornholm, it would seem more reasonable to interpret the facts as indicating a local uplift within the boundaries of the depositional area. This idea is expressed in the palaeogeographical map. It is quite likely that the area of uplift is substantially smaller than is shown on the map, as SORGENFREI and BUCH (1964) state that at Gassum there is probably a local structure, which can be interpreted as a deep-seated salt structure. In this case it may be reasonable to regard the lacuna in the sequence as the result of salt movements in Middle Jurassic times. It can be added that in the German and Polish salt dome province several examples of salt movements in the Jurassic are known (MEINHOLD et al., 1960; HORN, 1964; ZNOSKO, 1957).

It emerges from the preceding section that synsedimentary tectonics can be regarded as having had an important influence on the development of the sedimentation. This applies to the major features in the development of the depositional area, and also to the development of a local topography within certain parts of the basin.

Finally it can be mentioned that there are also numerous examples of tectonic structural changes in the area in the period after the formation of these particular sediments; that such movements can have had an influence on the present position of the deposits is obvious. The localities Ullerslev 1 and Rødby 1 can be given as examples; each of these must be presumed, at any rate in Rhaetic times, to have lain at about the same level in relation to sea level. The fact that the Rødby occurrence lies considerably higher than the Ullerslev occurrence (see fig. 3) must be attributed to later tectonic displacement, presumably caused by salt movements in the Rødby area.

THE DEVELOPMENT OF THE SEDIMENTATION

In accordance with what has been mentioned, it can be assumed that the Danish Embayment was to some extent developed as a tectonically built marginal subsidence along the flank of the Fennoscandian Shield. The presence of the Ringkøbing-Fyn High has given this area of subsidence the character of a strait, through which, at any rate during certain periods, there can have been exchange of water between the northern and eastern parts of the North European Basin. The northern part was presumably directly connected to a North Atlantic Ocean (see ARKELL, 1956, p. VIII) in the area between Scandinavia and Scotland; this can have had the result that the transgressions of a more high-sea character came from that side. In the picture of the north Europe of that period, the Fennoscandian land area obviously occupied a prominent place; it was presumably to a large extent material from this area that came to be deposited in the surrounding basins. In the period being considered here there was sedimentation over quite extensive areas of the North European Basin, namely, in addition to Denmark, also England (ARKELL, 1956), north Germany (ARKELL, 1956; BENTZ, 1959; MEINHOLD et al., 1960), Poland (POŻARYSKI, 1957; DADLEZ, 1957) and the eastern Baltic (KISNÉRIUS, 1960).

Rhaetic

At the start of Rhaetic times the Danish Embayment was obviously partly covered by the sea. This emerges most clearly in the western part of the area, where the marine, clayey Vinding Formation occurs, but in other areas also there is evidence of marine conditions. This applies, for instance, to Ullerslev 1, where the oldest Rhaetic consists of clay with a content of microfossils (ostracods) (CHRISTENSEN, 1962). Comparable clay deposits are found in the lowest part of the Rhaetic in several other wells whose microfossil content has however not yet been studied closely. On this basis it seems reasonable to assume that the Rhaetic sea came in, probably from the north-west, and invaded considerable areas of at any rate the central and southern parts of the basin.

At the same time, at some places along the margin of the basin, sandy deltaic deposits were evidently built out. It can be added here that during the transition from Middle Keuper to Rhaetic a change from dry to more moist climatic conditions is considered to have taken place. The moist climate would have meant an increased water flow in, and increased transporting ability for, the river systems. It is exactly this situation that is regarded as being the background for the delta formation that was so prominent in the area in Rhaetic times. In the Danish Embayment it is possible to distinguish between two different delta areas. The one, the "Ullerslev delta", seems to be of moderate size only; it is situated at the south-east end of the "Ringkøbing-Fyn island", and is regarded at present as having been built up by transport of material from this island. In the drainage area of this river system it is probable that it was in the main older sedimentary formations that were exposed.

At the same time a much larger delta, the "Gassum delta", was built up along the margin of the basin against Fennoscandia. It may have been built up at a place where more than one river system from Fennoscandia emerged into the Danish Embayment. The largest supply of material was obviously in the northern part of the area, where the delta seems to have had its most extensive development, but also farther south along the basin margin, e.g. in Skåne, there are sandy, non-marine deposits that can be regarded as delta-deposited; it should be noted that Bornholm seems to have lain outside the area of deposition in Rhaetic times. The river courses that led to the building up of the "Gassum delta" presumably drained those parts of the Fennoscandian land area that lay to the north and north-east of the Danish Embayment. The parts of Fennoscandia that were exposed in the area of fluviatile erosion consisted to a large extent of metamorphic complexes, but older sedimentary formations, possibly in the form of areas downfaulted into the basement, are also considered to have played some part. The basement in the northern part was rather rich in epidote and therefore presumably characterized by a lower grade of meta-

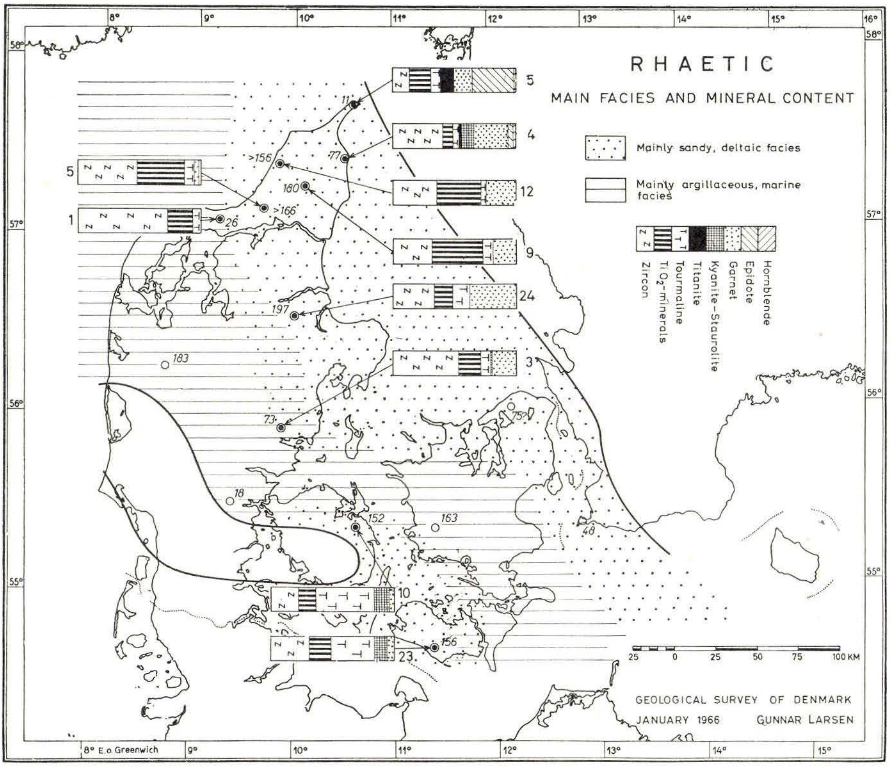

Fig. 44. Palaeogeographical map, Rhaetic. The figures beside the localities show the thickness in metres of the Rhaetic sequence. The figures beside the diagrams show the number of analyses on which the diagrams are based.

morphism than the area farther south, where epidote was evidently sparse, while garnet, on the other hand, was very prominent.

As to the nature of the delta, it can be assumed that the proximal parts were more or less covered by swamp forest; the Rhaetic coal in Skåne was presumably formed from such swamp-forest growth. Apart from this the plant remains that occur sparsely in the deltaic sediments seem to be redeposited fragments; both the fragmentary character and the fact that these plant remains appear especially in mica-rich sediments indicate this. The distal end of the delta was undoubtedly covered by the sea; the tracks of burrowing organisms, which are found here and there, are evidence of this. Whether the delta front had an unbroken, even course, or it had a lobate front caused by uneven supply of material has not yet been settled. An attempt has been made to show the main features of the Rhaetic sedimentation sketched here in the palaeogeographical map, fig. 44.

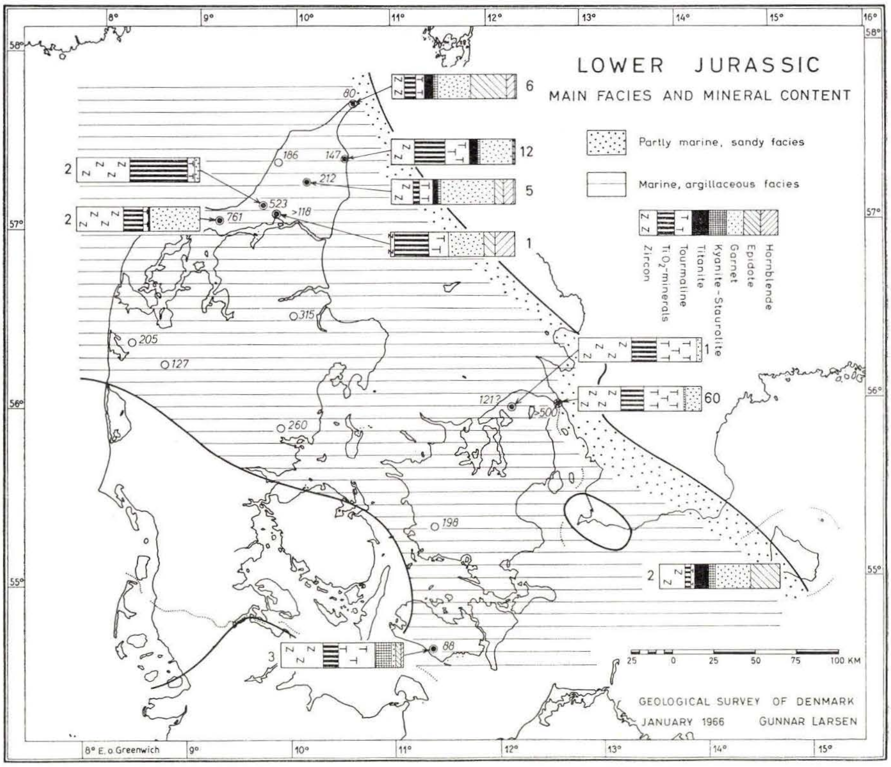

Fig. 45. Palaeogeographical map, Lower Jurassic. The figures beside the localities show the thickness in metres of the Lower Jurassic sequence. The figures beside the diagrams show the number of analyses on which the diagrams are based.

Lower Jurassic

The most characteristic feature of the development of the sedimentation in the Lower Jurassic is the extensive transgression that led to the whole of the Danish Embayment being covered by the sea. It can be stated here that according to MEINHOLD et al. (1960), it is possible in north-east Germany to trace how the sea gradually transgressed from west to east during Lias alpha. In the Danish Embayment it is likely that a certain belt including the locality Vinding 1, and probably Slagelse 1, was covered by the sea from the start of Rhaetic times, and that there was probably, during the rise of the sea in the Lower Jurassic, a transgression from this zone over the adjacent north-eastern and south-western border zones of the basin. In Øresund, near the edge of the basin, there is evidence that the transgression first reached the area in Lias alpha-3, and it first reached Bornholm in Lias gamma. In Øresund and the adjacent parts of Skåne, there was evidently, before the Lias transgression, a rather large area with river outlets giving rise to delta formation where smaller marine incursions occurred from time to time; the development in Bornholm seems to have been similar and presumably the same situation occurred at several other places along the coast of Fennoscandia.

In the basin as a whole, the deposits laid down under marine conditions were generally clayey; these are usually dark-coloured and rather rich in pyrite, which can indicate that ventilation and water circulation were rather restricted. In the coastal area in the Øresund region, there was, on the other hand, a greater variation in facies; for one thing, there are intercalations of non-marine sediments in the marine sequence, and for another, the marine deposits vary in grain size, ranging from coarse sand to clay; other places in the coastal zone must be presumed to have undergone a similar development.

As mentioned earlier (p. 33), it is possible that these changes in the nature of the sedimentation in the coastal zone can be correlated with the variations in content of silt and fine sand that have been detected at certain places within the otherwise mainly clayey basin deposits. If so, this presumably reflects variations in the extent of the sea during that period. In this connection it can be mentioned that HALLAM (1964) has the opinion that in the course of the Lower Jurassic there occurred throughout considerable parts of north-west Europe several transgressions and regressions determined by eustatic changes in sea level. In this particular area it must however be taken into account that local tectonic conditions can also have played a part; according to BÖLAU (1954, 1959) there are clear examples in north-west Skåne of synsedimentary tectonic activity in the Lias.

Because there are in the northern part of the depositional area, as well as in the area near the Ringkøbing-Fyn High, approximately the same mineral assemblages in the Lias as in the underlying Rhaetic sediments, it is considered likely that the supply of material to the basin took place from the same areas and through the same river systems as in the Rhaetic. The materials that were deposited in the south-eastern border area of the basin are considered for the time being, as are the deposits farther to the north-west, to have been brought by rivers from the Scandinavian area; the Bornholm material is derived presumably from a gneiss area situated in the southern part of Fennoscandia (perhaps directly connected to the present Bornholm), while the material in the Øresund area seems to be derived from older sedimentary formations; whether these were situated within Fennoscandia proper, or, and this is perhaps more likely, in the adjacent part of the Baltic area, must remain an open question for the time being.

In the river systems that already existed in the Rhaetic, the Liassic rise in sea level mentioned on p. 91 probably resulted in such changes in the erosional base-level that considerable amounts of sediment were deposited in the original river courses; i.e. the Lower Jurassic depositional area presumably had off-shoots in the Fennoscandian area. No attempt has been made, however, to

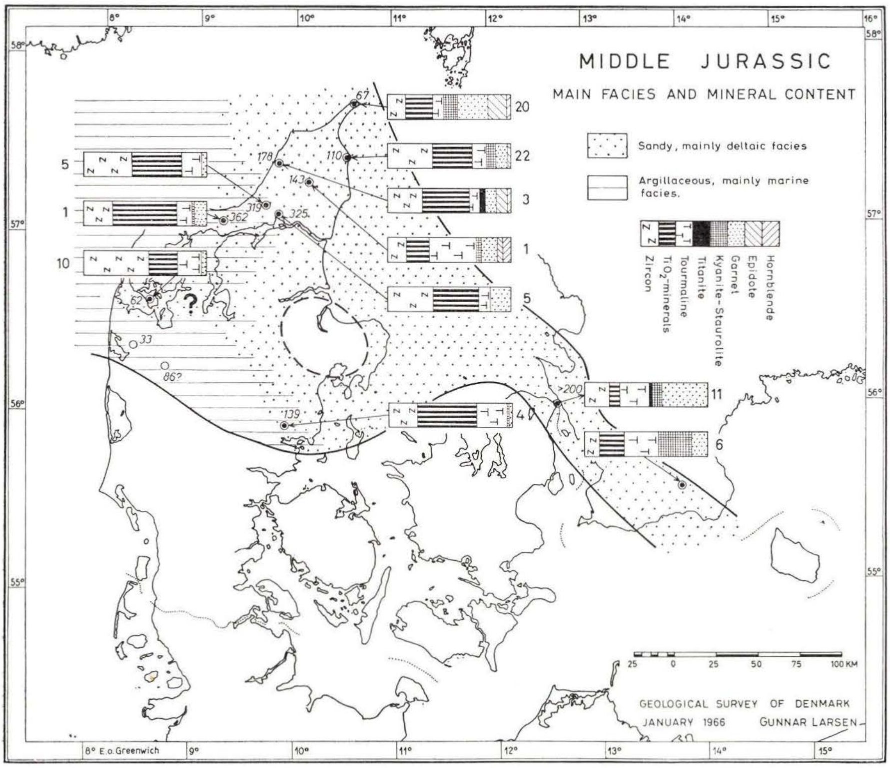

Fig. 46. Palaeogeographical map, Middle Jurassic. The figures beside the localities show the thickness in metres of the Middle Jurassic sequence. The figures beside the diagrams show the number of analyses on which the diagrams are based.

express this on the map, fig. 45, which only sketches the palaeogeography of the Lower Jurassic in a very simplified, schematic form.

Middle Jurassic

The most prominent feature in the geological development in the Middle Jurassic seems to be the considerable regression that took place, and the reduction in the depositional area, possibly as a consequence of this (see fig. 46). The Dogger deposits are thus mainly restricted to the north-western part of the Danish Embayment, and to an evidently narrow strait stretching from this area over Øresund to Bornholm; this strait presumably represents, as mentioned earlier, a tectonic subsidence zone. It should be emphasized that it is possible that later erosion has removed originally more extensive Dogger deposits.

The regression obviously did not affect the entire area immediately at the start of Middle Jurassic times. In the more central part of the north-western depositional area, the marine clay sedimentation continued without change, and in the Øresund area, which was presumably rather close to the coast, the

Dogger evidently commenced with a marine transgression. This was presumably a rather brief episode, however, since the succeeding deposits seem to have been formed in a deltaic area that had local plant growth, probably of swamp-forest type, judging by the occurrence of rather thick coal seams with accompanying seat-earth beds in the Øresund boring no. 7. Comparable deltaic deposits ("Haldager delta") also developed outwards from the Fennoscandian coast into the north-west part of the Danish Embayment; these deposits probably originated to some extent through the supply of material from the same areas and by the same river systems as in the Rhaetic and the Lias. The zones with mineral assemblages more resistant to weathering, which appear locally in the deltaic deposits, are believed to be a reflection of weathering, erosion and redeposition of Lower Jurassic river sediments, determined by the Middle Jurassic fall in sea level (see p. 92). It cannot be excluded however that weathering may have taken place after deposition in the delta, since certain parts of the delta were presumably subaerially exposed; there is direct evidence, in the form of sporadically occurring, weathered glauconite grains, that such an in situ weathering did take place. The presence of glauconite can moreover indicate a certain amount of marine influence, a concept that is supported by the occurrence of remains of foraminifera here and there. It is considered likely that considerable areas in the distal part of the delta were covered by the sea, so that it is hardly possible to distinguish between those deposits that were formed in the delta front itself, and those that belong to the sea bed ahead of the delta.

It seems that non-marine sand deposits occur as far west in the basin as Uglev 1. To what extent this really indicates a western offshoot of the "Haldager delta", or whether the sand represents older sediments that have been redeposited as a result of the rise of the salt dome to the erosional level in Middle Jurassic times must be regarded as an unsolved problem for the time being. In other places also, salt movements seem to have led to the formation of some degree of relief in the bed of the basin. The island that is believed to have existed in the area of Gassum at that time may have appeared as a result of salt movements.

In the deeper part of the basin the sandy deltaic deposits are overlain by marine clay, which can indicate that a rise in sea level began to take place towards the close of the Middle Jurassic.

Upper Jurassic

It seems that in the Upper Jurassic the development that characterized the preceding period continued without a break, so that the sea came to cover the whole of the northern part of the Middle Jurassic delta area. In the course of the transgression, furthermore, the "Gassum island" became covered by the sea; the fact that red variegated beds appear in Gassum 1 may indicate that there was still a land area here at the beginning of the Upper Jurassic, but it is

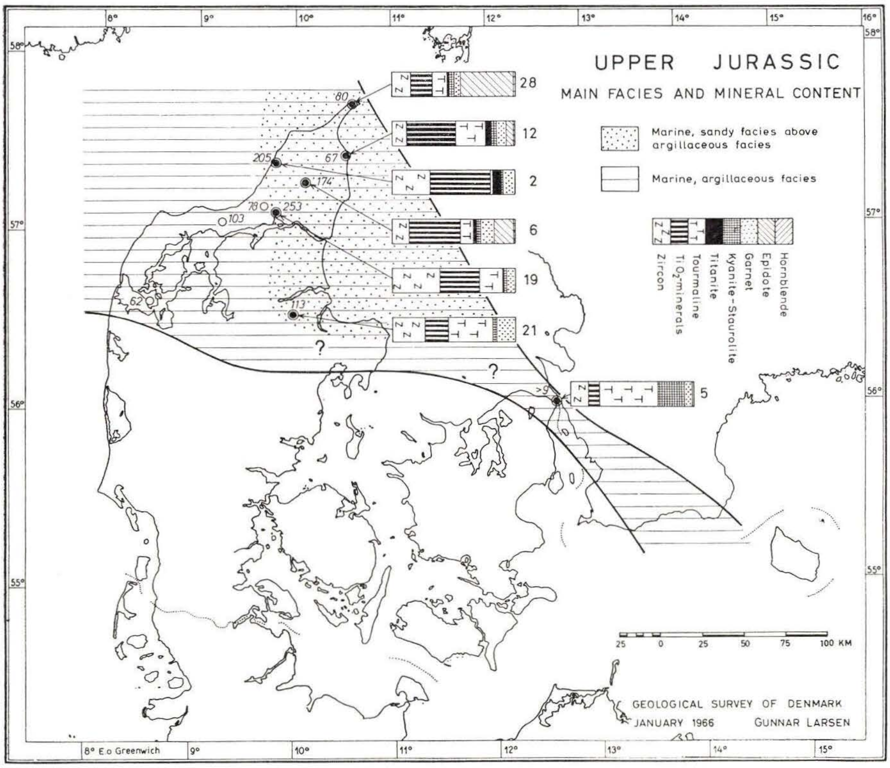

Fig. 47. Palaeogeographical map, Upper Jurassic. The figures beside the localities show the thickness in metres of the Upper Jurassic sequence. The figures beside the diagrams show the number of analyses on which the diagrams are based.

also possible, however, that the variegated material represents the redeposited remains of a Middle Jurassic weathered surface.

While the northern part of the area was clearly affected by a rise in sea level, there seems to have been a regression farther south, so that the Upper Jurassic depositional area actually appears to be reduced in size compared with the Middle Jurassic depositional area (figs. 46 and 47); it is possible that these features indicate that a tectonically determined uplift of the southern part of the Danish Embayment took place at that time. This uplift can hardly have affected the Fennoscandian Border Zone, which, particularly in the Upper Jurassic, continued as an area of deposition.

The Upper Jurassic seems everywhere, at any rate in the depositional area in north Jylland, to commence with clayey, marine deposits; in the parts nearer the margin this clay material seems in places to be characterized by greenish tints, while this is less true of the deposits in the deeper part of the basin. Here in the deeper part, so far as can be seen, the clay sedimentation continued without a break throughout the entire Upper Jurassic, while nearer the coast, towards Fennoscandia, a change in the type of sediment, from clay to sand, occurs at the transition from the Oxfordian to the Kimmeridgian. The sand is clearly marine, as shown by the content of both fossils and glauconite; it is also the first time that glauconite appears in larger amounts in this sequence. The sand sedimentation seems to have taken place in a ca. 100 km broad zone along the north-eastern margin of the basin, but has not been traced farther to the south-east. It is possible that the locality Skagen 2 represents a part of the coastal area itself; the weathered glauconite grains that occur here suggest at any rate that the area has been subaerially exposed at times.

It seems that after this in the Upper Jurassic it is possible to distinguish between the following three depositional environments in the northern depositional area: 1) A beach zone with sand deposits, 2) a broad, possibly rather shallow-water zone along the coast, where, under the influence of water movements, rather uniform, sorted sandy material was deposited and 3) an area of clay sedimentation farther west, where the depth of water was presumably greater and the water movement less. It must be added that there has presumably also been a rather large area with river outlets in this coastal belt. Evidence in support of this idea is provided by the fact that the mineral content in the Upper Jurassic in north Jylland matches that found in the older deposits so well that they must be regarded as having the same origin. The sediments farther south, for instance at Gassum, have a somewhat different mineral assemblage and are therefore possibly derived from other source material (perhaps redeposited Dogger sediments of south-eastern origin?).

In the marine Upper Jurassic there are locally considerable amounts of plant material. This may stem from plant growth in the adjacent land areas. If so, the climate in the Upper Jurassic, as in the preceding parts of the Jurassic and the Rhaetic can be regarded as having been moist. This would in a way agree very well with what SORGENFREI (1963) has pointed out, that in this depositional area, in contrast to the depositional area in north-west Germany, (see RICHTER-BERNBURG, 1953), no sign of evaporite formation has been found in the Upper Jurassic.

Lower Cretaceous

The transition from the Upper Jurassic to the Lower Cretaceous is almost imperceptible in the development of the sedimentation in the north-western part of the depositional area, far from the coast; in this area the clay sedimentation continued as before. In the marginal areas of the basin, on the other hand, more pronounced changes occur. Along the boundary of the basin with Fennoscandia a distinct regression is thus traceable and in the course of the Lower Cretaceous a transgression resulted in substantial areas of the formerly elevated parts of the Danish Embayment being covered once more by the sea; the transgression commenced already during the Valanginian (see Vinding 1).

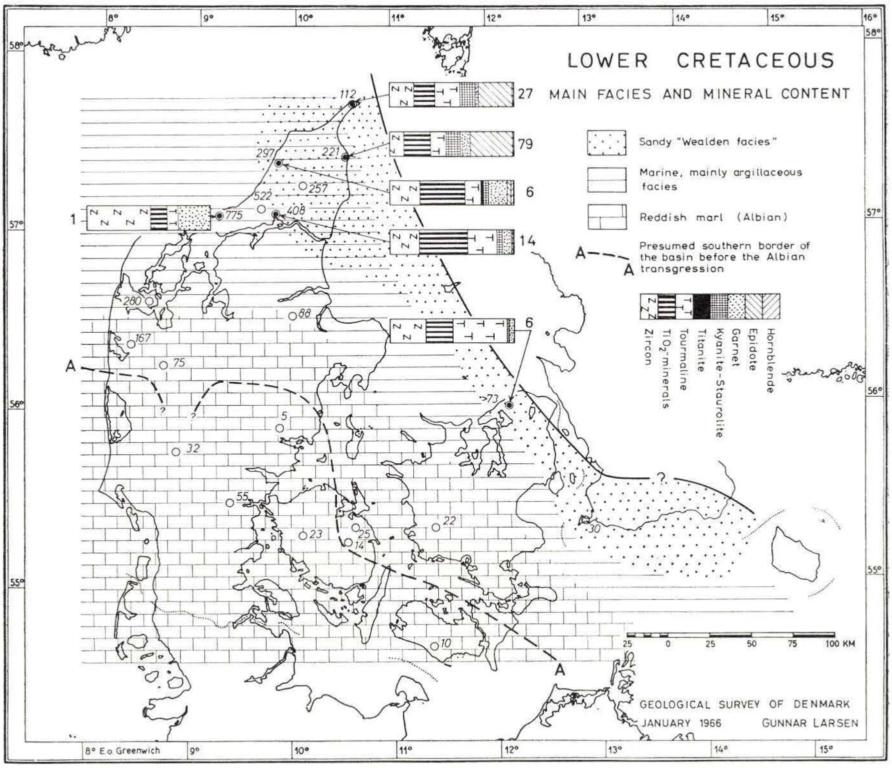

Fig. 48. Palaeogeographical map, Lower Cretaceous. The figures beside the localities show the thickness in metres of the Lower Cretaceous sequence. The figures beside the diagrams show the number of analyses on which the diagrams are based.

It seems logical to explain this development as being partly the result of tectonic events, namely, an uplift of Fennoscandia relative to the Danish Embayment. The boundary between the area of uplift and the area of subsidence presumably followed more or less the belt that featured as a zone of subsidence along the edge of Fennoscandia during the Middle and Upper Jurassic (see fig. 46 and 47); the presence of the large flexure in the Øresund area and in the part of Skåne immediately to the south-east indicates this. To what extent this deformation took place just at the transition from Jurassic to Cretaceous has not, as mentioned, been demonstrated with certainty, but several facts seem to suggest that this could be so.

The regression that, as mentioned, set in along the border of Fennoscandia resulted in north Jylland in non-marine sandy material being spread out over the marine Upper Jurassic deposits. It is probable that this material represents a deltaic deposit around the mouth of a river, similar to those deposits formed earlier in this area; this is indicated by the mineral content. The zone with minerals stable under weathering, which occurs in these beds, is believed to represent redeposited flood-terrace sediments (cf. p. 92). This "Skagen delta" must undoubtedly be referred to the group of "Wealden deltas" that were developed at several places in the north European depositional area during this period (see MARLIERE, 1963; TAYLOR, 1963; THIERMANN and ARNOLD, 1964). Comparable deltas are encountered at other places along the edge of Fennoscandia, namely, in Bornholm (GRY, 1956) and also at Höllviken (BROTZEN, 1950) and Lavø; it should be noted that the mineral assemblage at Lavø can reasonably be considered to represent weathered, redeposited material from the Jurassic beds of the Øresund area. It is possible that the Wealden occurrences mentioned here are merely part of a more or less continuous border facies along the boundary of the basin with Fennoscandia; this is indicated on the map, fig. 48.

At the same time as this Wealden facies was being developed, there took place, as mentioned, a marine sedimentation farther out in the basin, and presumably parts of the deltas were covered by the sea. In north Jylland there is clear evidence showing that during the Lower Cretaceous the sea transgressed over considerable areas of the "Skagen delta", so that the delta became covered by marine, glauconite-rich sediments. Presumably this transgression in north Jylland was matched by a similar transgression in the southern part of the basin, so that the south part can have been covered by the sea as far south as the line A–A on the map, fig. 48. This can, however, only be a hypothesis for the time being; its verification must await more precise dating of the beds. In north Jylland the transgression was succeeded by a minor regression so that non-marine deposits came to overlie the marine beds (e.g. in Frederikshavn City 1); it is possible that this is a purely local phenomenon, but it seems possible nevertheless to conclude from this that "Wealden facies" was not only connected with the oldest part of the Lower Cretaceous, but was probably characteristic of the major part of that period.

Up till this stage the pattern of sedimentation in the Lower Cretaceous in the main matched very closely the pattern in the Rhaetic and the Jurassic. In the last part of the Lower Cretaceous, the Albian, a change began to take place. For one thing, a very comprehensive transgression set in, so that the entire area, not only the Danish Embayment, but also the Ringkøbing-Fyn High, was covered by the sea, and for another, with this transgression the terrigenous sedimentation was replaced by calcareous sedimentation. This resulted in reddish marl being deposited over both the structural high and the south-west part of the embayment (see fig. 48). It should be noted that the red coloration can be derived from the carrying into suspension of material from the weathered surface that probably covered considerable parts of the land area that the sea invaded (see Rødby 1). These marl deposits are not encountered right in at the edge of the basin; the reason for this is presumably that in the Albian so much terrigenous material was still being brought from Fennoscandia that the calcareous sedimentation could not become established in this area. However, the transgression itself must have asserted itself, something that is shown by the occurrence of the upper glauconite horizon in Frederikshavn City 1. The radiolaria-bearing bands that appear in this glauconite zone seem to indicate that with this transgression marine conditions set in that were of a more high-sea type than those encountered previously in the area. A transgression corresponding to that sketched here is encountered in the adjacent areas to the south-east (see CIEŚLIŃSKI, 1960).

It thus appears that the sedimentological-palaeogeographical development that had characterized the Danish Embayment since the Rhaetic came to a close in the Albian. The Albian transgression signifies in fact the introductory phase of a new sedimentological-palaeogeographical situation, which came to characterize the area during the whole of the Upper Cretaceous.

CONCLUDING REMARKS

It has been the intention in making these investigations to try to throw light on the history of the sedimentation in the Danish Embayment during Rhaetic, Jurassic and Lower Cretaceous times. This has been possible to a certain extent, but various problems have not yet been cleared up. This is partly because the investigations within the limits laid down could not deal with all aspects of the nature of this sedimentary material. Amongst the tasks still remaining, the following can be named:

1) clay-mineralogical studies to elucidate the composition, origin and conditions of formation of the fine-grained sediments,
2) thin-section investigations to help in unravelling the details of the course of diagenesis,
3) ore-microscopic analyses to provide information about the types of opaque grain, possible alteration and other features,
4) extended geochemical analyses, for example of the organic content of the clays.

It should be noted about 4) that such analyses can eventually have importance in assessing whether hydrocarbons are developed in this sequence. So far as is known up till now the question has only been assessed in the light of general considerations, for example: a) certain clay formations seem to be bituminous, although hardly to the same extent as the north German Posidonienschiefer (see VON GAERTNER, 1955); b) the major features in the development of the sedimentation in this area appear, especially in the Lower and Middle Jurassic, to match rather closely the conditions in the North German Basin (SORGENFREI, 1963), where hydrocarbons have been found (see HARK, 1966); c) brown, grey and black clay deposits, which can be source beds for oil (see HUNT, 1966) occur frequently in the depositional area that has been studied.

In addition to the above list of tasks that require to be performed, another can be mentioned

5) additional heavy-mineral analyses of the older sedimentary formations in the Danish Embayment and also in the Ringkøbing-Fyn High and in Fennoscandia; the reason for doing this would be to try to throw light on the problem of which sedimentary formations were exposed and redeposited during the development of the sedimentation in the Rhaetic, Jurassic and Lower Cretaceous.

By making such studies in the future, it should be possible to make important additions to the picture of the history of sedimentation that has been obtained from these investigations.

APPENDIX

ANALYSES OF A FEW SELECTED SEDIMENTARY SAMPLES FROM SKÅNE

In connection with these investigations of material from the borings in the Danish Embayment, a few samples from surface exposures in Skåne were analysed; the analytical procedure was exactly the same as described on pp. 14–16.

A. The Kågeröd Formation at Ottarp. The study material consisted of a single sample of the rather coarse-grained arkose found in the Kågeröd Formation (Keuper), from the outcrop at the top of the slope south-west of Ottarp church. The sample was collected in May 1965, during an excursion led by E. MOHRÉN (see MOHRÉN, 1966). The analysis showed that there was a quartz/feldspar ratio of 1,1 and that the non-opaque heavy fraction had the following composition:

Zircon:	2%
TiO_2-minerals:	+
Garnet:	98%

The comments on p. 95, and fig. 43, p. 79 should also be noted in this context.

B. The glass sand in Fyledalen. The study material consisted of six samples collected by professor, dr. phil. TH. SORGENFREI and cand. mag. BRUNO THOMSEN in April 1964. The samples are from the steeply dipping sand bed in the Fyleverken sandpit at Eriksdal station; the positions of the samples in relation to the coal seams that occur there are as follows:

(highest) sample no. 6: Light grey sand above thick coal seam no. 3.
sample no. 5: Grey sand between thin coal seam no. 2 and thick coal seam no. 3.
sample no. 4: Grey, coarse and clayey sand just above the thin coal seam no. 2.
sample no. 3: Grey sand above coal seam no. 1.
sample no. 2: Grey sand, ca. 1.5 m above the boundary with the underlying light-coloured sand, and below coal seam no. 1.
(lowest) sample no. 1: Light-coloured sand below the grey, coal-bearing sequence.

The following grain size distribution was revealed by the analysis:

	< 75 μ	75–250 μ	> 250 μ
Sample no. 6	29%	69%	2%
Sample no. 5	56 –	43 –	1 –
Sample no. 4	6 –	11 –	83 –
Sample no. 3	5 –	10 –	85 –
Sample no. 2	20 –	79 –	1 –
Sample no. 1	2 –	98 –	– –

The light fraction contains some plant remains as well as a little mica; the following values were found for the quartz/feldspar ratio:

Sample no. 6: 13.3
Sample no. 5: 11.5
Sample no. 4: 32.5
Sample no. 3: 99.0
Sample no. 2: ∞
Sample no. 1: 99.0

The heavy fraction contains from 40 to 90% opaque grains; in addition much mica occurs, particularly in the highest two samples. The following distribution was found for the remaining non-opaque minerals:

Sample no.	Zircon	TiO_2-minerals			Tourmaline	Staurolite	Kyanite	Chloritoid	Garnet	Other minerals
		Anatase + brookite	Fine-grained aggregates	Rutile						
6	8%	2%	6%	22%	25%	5%	11%	1%	20%	+%
5	15 –	5 –	10 –	28 –	16 –	1 –	6 –	– –	17 –	2 –
4	3 –	– –	– –	1 –	20 –	21 –	30 –	– –	25 –	– –
3	14 –	– –	1 –	4 –	30 –	15 –	21 –	– –	15 –	– –
2	27 –	1 –	6 –	15 –	35 –	9 –	7 –	– –	– –	– –
1	6 –	– –	6 –	10 –	45 –	12 –	21 –	– –	– –	– –

Fig. 40 (p. 71) and the comments on p. 79 should be noted in this context.

DANSK SAMMENDRAG

RHÆTISKE – JURASSISKE – NEDRE KRETACISKE SEDIMENTER I DET DANSKE SÆNKNINGSOMRÅDE (EN TUNGMINERALUNDERSØGELSE)

Indledning

Kendskabet til Danmarks dybere undergrund skyldes i alt væsentligt den efterforskning efter olie, gas. m.v., som Danish American Prospecting Co. med visse afbrydelser udførte i årene 1935–1959 (jvf. SORGENFREI og BUCH, 1964). – Det herved tilvejebragte materiale findes nu på D.G.U., hvor en arbejdsgruppe under professor TH. SORGENFREI's ledelse i februar 1962 påbegyndte en bearbejdelse. Som medlem af denne gruppe har forfatteren specielt varetaget den sedimentpetrografiske side af studiet af de rhætiske, jurassiske og nedre kretaciske aflejringers geologi. Det er resultaterne heraf, som fremlægges i den her foreliggende afhandling. – Denne undersøgelse har været tilrettelagt således, at en speciel analyse af sedimenternes tungmineralindhold har været kombineret med en gennemgang af lagseriens almene lithologiske og stratigrafiske forhold; hensigten hermed har været at søge visse træk af disse aflejringers oprindelse og dannelsesforhold belyst. Undersøgelsen har på indeværende tidspunkt ikke omfattet hele landet, men har væsentligst vedrørt forekomsterne i det Danske Sænkningsområde, d.v.s. det aflejringsområde som mod NØ grænser op mod den Fennoscandiske Randzone og mod SV er delvis adskilt fra det nordtyske aflejringsfelt af Ringkøbing-Fyn Højderyggen, se fig. 1, p. 10.

Materiale og metode

Undersøgelsen omfatter et antal boringer, som er ført ned i eller gennem rhæt – jura – nedre kridt lagserien. Fra visse af boringerne findes et stort antal kerneprøver, fra andre kun ret få, og enkelte er slet ikke kerneboret i det interval, som behandles her.

Vurderingen af lagseriens almindelige lithologi er baseret ikke blot på kernematerialets udsagn men tillige på beskrivelser af skylleprøver samt på Schlumbergerkurverne. Til petrografisk analyse benyttedes derimod udelukkende materiale fra borekernerne.

De af kernematerialet udtagne analyseprøver (ialt ca. 1500 stk.) blev først delt; den ene del blev henlagt som referensprøve, medens resten blev taget i arbejde; på en mindre del af sidstnævnte bestemtes karbonatindholdet, samtidig med at hovedparten præpareredes til petrografisk analyse. Præparationen omfattede først en opdeling efter kornstørrelse, nemlig $< 75\ \mu$, $75–250\ \mu$, $> 250\ \mu$. Fraktionen $75–250\ \mu$ blev derpå behandlet med syre for at fjerne evt. indhold af karbonat samt jernforbindelser fra kornoverfladerne, hvorpå den opdeltes i en let og en tung fraktion v. hj. a. bromoform. Af disse to fraktioner fremstilledes mikroskoppræparater, som derpå undersøgtes v. hj. a. polarisationsmikroskop; herved identificeredes materialets indhold af mineraler og bjergarter, og disse komponenters mængdeforhold bestemtes ved korntælling.

Præsentation af analyseresultaterne

Ialt 15 dybdeboringer er undersøgt efter den ovenfor omtalte metode; resultaterne er fremlagt i profildiagrammerne, tavle II–XVI. Disse er suppleret med tavle XVII, omhandlende tilsvarende data fra de tidligere undersøgte Øresundsboringer (LARSEN et al., 1965). Den til disse tavler hørende signaturplan er vist i tavle I.

De enkelte diagrammer er indrettet således, at udgangspunktet er et lithologisk profil, ledsaget af beskrivelser og Schlumbergerkurver. Længst til venstre er den stratigrafiske inddeling anført; denne inddeling er baseret på NØRVANG (1957) samt SORGENFREI og BUCH (1964). Det skal bemærkes at den for tiden på D.G.U. igangværende biostratigrafiske bearbejdelse af disse materialer formentlig vil føre til visse revisioner m.h.t. lagseriens stratigrafiske inddeling. – Til højre for profilet med tilhørende Schlumbergerkurver følger resultaterne af de petrografiske analyser. Her er først anført prøvematerialets lokalisering og dernæst en oversigt over bjergartsfarven, hvor der for hver prøve med fuldt optrukken streg er markeret hovedfarven, medens en punkteret streg angiver bifarven. Siden følger et diagram for karbonatindholdet og et for kornstørrelsesfordelingen; for sidstnævnte gælder, at kun uhærdnede sedimentprøver er medtaget. De resterende diagrammer omhandler alle mineralindholdet i kornfraktionen 75–250 μ. Det første af disse viser hovedsammensætningen af det lette materiale, nemlig mængdefordelingen af flg. komponenter: Glauconit, fossilrester, diverse aggregater, glimmer, kvarts + feldspat og planterester; derpå følger et specialdiagram, nemlig for forholdet kvarts/feldspat (sml. fig. 2, p. 20). Den tunge fraktions hovedsammensætning er emnet for næste diagram, hvor der er skelnet mellem fire korngrupper: Pyrit med organismestruktur, andre opake korn, glimmer og andre non-opake korn. Mineralfordelingen i denne sidstnævnte korngruppe er vist i de følgende diagrammer; stedvis, hvor kornantallet har været for ringe til procentudregning, er der blot med + markeret tilstedeværelsen af mineralerne. I den sidste rubrik „Remarks" er angivet forekomsten af visse mineraler, som ikke er medtaget ved de kvantitative analyser.

Lagseriens lithologi og stratigrafi

I dette afsnit søges lagseriens lithologiske udvikling anskuet i sammenhæng med de stratigrafiske forhold. Denne redegørelse tager sit udgangspunkt i den forenklede profiloversigt, fig. 3 (p. 22); af oversigtsmæssige grunde opstilles der et antal lithostratigrafiske formationer, hvis repræsentation i de forskellige boreprofiler er angivet i tabel I, side 43. Til disse formationer skal knyttes flg. kommentarer:

Vinding formationen: overvejende lerede, marine aflejringer af rhætisk alder; knyttet til den vestlige og mere centrale del af bassinet.

Gassum formationen: overvejende sandede, ikke-marine, øjensynlig deltaiske aflejringer af rhætisk alder; knyttet til bassinets nordlige randområde.

Ullerslev formationen: overvejende sandede, ikke-marine, øjensynlig deltaiske aflejringer af rhætisk alder; knyttet til bassinets randområde mod Ringkøbing-Fyn Højderyggen.

Fjerritslev formationen: overvejende lerede, marine aflejringer af nedre jurassisk og stedvis også mellem jurassisk alder; forekommer praktisk taget over hele aflejringsområdet.

Haldager formationen: overvejende sandede, ikke-marine, øjensynlig deltaiske aflejringer af mellem jurassisk alder; formentlig oprindelsesmæssigt knyttet til bassinets nordøstlige randfelt.

Børglum formationen: overvejende lerede, marine aflejringer af øvre jurassisk og stedvis tillige mellem jurassisk alder; vidt udbredt i bassinet.

Frederikshavn formationen: overvejende sandede, marine aflejringer af øvre jurassisk alder; knyttet til den nordøstlige del af aflejringsområdet (se fig. 15, p. 37).

Skagen formationen: overvejende sandet, ikke-marin, øjensynlig deltaisk aflejring af nedre kretacisk alder; knyttet til den nordøstlige del af aflejringsområdet (se fig. 15).

Vedsted formationen: overvejende leret, marin aflejring af nedre kretacisk alder; vidt udbredt i aflejringsområdet.
Lavø formationen: overvejende sandet, i hvert fald til dels ikke-marin aflejring af nedre kretacisk alder; knyttet til østlige randfelt.
Rødby formationen: overvejende rødlige, marine mergel- og kalkaflejringer, hvis alder er albien (enkelte steder også aptien); optræder i den sydligere del af bassinet samt over Ringkøbing-Fyn Højderyggen.

Eksempler på sedimentmaterialet, der indgår i nogle af disse formationer, er vist i fig. 4–16 (pp. 24–39).

Lagseriens mineralindhold

Dette afsnit indledes med en omtale af de forskellige mineraler og mineralgrupper; det er især sådanne karakterer, som tillægges betydning for vurderingen af disse komponenter som sedimentære bestanddele, der er gjort rede for. Dette stof er ledsaget af nogle fotografier af de forskellige slags mineralkorn (fig. 17–38, p. 44–66).

Derpå følger en gennemgang af mineralselskabernes fordeling; til støtte herfor er fig. 39–48 fremstillet. Hovedtrækkene i mineralfordelingen kan angives således:

Ved den nordlige bassinrand findes et epidotrigt selskab, som gør sig mere eller mindre stærkt gældende gennem hele den her foreliggende aflejringsperiode. Et tilsvarende selskab træffes øjensynlig også i lias på Bornholm (jvf. WEYL og WERNER, 1952). I Øresundsforekomsten, beliggende midt imellem de nordjyske lokaliteter og Bornholm, er der imidlertid ingen antydning af et sådan epidotselskab. – I Nordjylland spores en reduktion i epidot-hyppigheden fra bassinranden og ud i den mere centrale del af aflejringsområdet. Her er de rhætiske aflejringer (Gassum formationen) præget af et temmelig stort granatindhold (undtagelser: Vedsted og Fjerritslev) samt af, at zirkon er hyppigere end turmalin (fig. 41); endvidere er disse aflejringer rige pa feldspat. De jævnaldrende dannelser ved randen af Ringkøbing-Fyn Højderyggen (Ullerslev formationen) afviger fra de ovennævnte ved at være fattigere på feldspat og granat samt ved at indeholde relativt meget mere turmalin (fig. 41); endvidere spiller kyanit og især staurolit en større rolle her (fig. 40). De to formationer er således tydeligt forskellige og udgør øjensynlig hver sin tungmineralprovins. – For liaslagene (Fjerritslev formationen) synes det gennemgående træk at være, at tungmineralsammensætningen i hovedsagen svarer til den i de underliggende rhætiske aflejringer; de mineralprovinser, som var etableret i rhæt, synes således at holde sig nogenlunde uændret i lias. Øresund-Lavø området, hvorfra man endnu ikke kender det rhætiske mineralselskab, har en tungmineralassociation i nedre jura, som ikke helt kan indpasses i de ovennævnte mineralprovinser; der er derfor muligvis tale om en særlig, østlig provins. – Den mellem jurassiske Haldager formation er i det store og hele ret fattig på feldspat; granatindholdet er gennemgående mindre end i de underliggende aflejringer, medens de stabile mineraler er mere fremtrædende. De jævnaldrende aflejringer i Øresundsområdet er tydeligt afvigende herfra, især ved at have et stort granatindhold, men også ved at staurolit og kyanit gør sig noget stærkere gældende. – I øvre jura er den regionale variation i mineralsammensætningen i store træk som tidligere: En nordlig epidotpræget provins, en sydfor liggende provins med et mere stabilt tungmineralselskab og endelig en østlig provins (Øresund), karakteriseret ved et ret stort turmalin- og kyanitindhold. – I nedre kridt er der stort set en lignende fordeling; dog er kendskabet til den østlige provins meget ringe.

Det ser således ud til, at der indenfor det undersøgte aflejringsområde kan udskilles visse regioner, hvis mineralsammensætning ganske vist ændrer sig op igennem lagserien, men hvis indbyrdes særpræg i store træk bibeholdes.

Årsagen til den fundne mineralfordeling må søges i en kombineret virkning af mange forskellige faktorer; disse kan indordnes i flg. hovedgrupper:

Udgangsmaterialets sammensætning
Forvitringsprocessernes indvirkning
Transport- og aflejringsprocessernes indvirkning
Diageneseprocessernes indvirkning.

I observationsmaterialet foreligger indicier på diagenesens indflydelse, dels i form af authigen mineraldannelse (bl. a. pyrit, tungspat, TiO_2-mineraler, kvartsudvoksninger på kvartskorn, kalkcementering) og dels i form af mineralopløsning (korrosionsmærker på epidot, granat, staurolit, kyanit, titanit). Med udgangspunkt i bl. a. WIESENEDER's oversigt over emnet (WIESENEDER, 1953) diskuteres det spørgsmål, om den destruktive diagenese har medført gennemgribende ændringer i det oprindelige mineralselskabs sammensætning. Den opfattelse, der herved fremkommer, er, at den diagenetiske opløsning lokalt har været meget dybtgående, eksempelvis i rhæt i Vedsted; men i det store og hele kan den regionale variation i tungmineralfordelingen næppe regnes for at være et udslag af diageneseprocessernes virkning.

Under transport- og aflejringsprocesserne er der utvivlsomt sket dels en nedslidning af kornene og dels en udsortering af disse efter størrelse eller masse. Den forskel, der stedvis kan iagttages i henholdsvis finkornede og mere grovkornede sedimenters mineralindhold, skyldes sandsynligvis sådanne processers indvirkning. De større træk i mineralfordelingen kan dog ikke forklares på denne måde, men må ses som resultatet af, at der er sket en materialtilførsel fra flere forskellige områder af indbyrdes forskellig sammensætning. Mineralselskaberne i den nordlige og østlige del af aflejringsfeltet er utvivlsomt tilført fra Fennoscandia gennem flere større og mindre flodløb. Mineralselskaberne i aflejringerne omkring Ringkøbing-Fyn Højderyggen hidrører antagelig fra denne højdestruktur.

I de nordjyske forekomster er „ustabile" mineraler (såsom feldspat, epidot og granat) i det store og hele ret hyppigt forekommende, hvilket tyder på, at disse sedimentmaterialer ikke har været udsat for en intensiv kemisk forvitringsproces. En undtagelse udgør dog bl. a. den mellem jurassiske Haldager formation, hvori der optræder en zone med lavt indhold af både feldspat og ustabile tungmineraler, hvilket tydes som resultat af forvitringspåvirkning; muligvis står vi overfor en af den mellem jurassiske havspejlssænkning betinget forvitring og omlejring af nedre jurassiske flodsengssedimenter. En analog oprindelse har muligvis også en zone med stabile mineraler i den nedre kretaciske Skagen formation. Endvidere skal nævnes, at der også hist og her findes symptomer på in situ forvitring af aflejringerne.

Sedimenterne stammer tydeligvis fra flere forskellige udgangsmaterialer, omfattende både krystallinske massiver og sedimentære formationer. Epidotselskabet i det nordjyske område har utvivlsomt sin oprindelse i et Fennoscandisk gnejsfelt, metamorfoseret i epidotamfibolit facies. Det granatrige selskab, som gør sig gældende i rhæt-lias lagserien syd for epidotprovinsen, stammer sandsynligvis også fra Fennoscandiske, krystallinske udgangsmaterialer, formentlig af mere højmetamorf natur end ovennævnte. For begge de omtalte selskaber gælder endvidere, at de også indeholder visse komponenter, som sandsynligvis må afledes fra ældre sedimenter. Rhæt-lias sedimenterne ved Ringkøbing-Fyn Højderyggen regnes for i det væsentlige at bestå af omlejrede sedimentære formation, som formentlig har været lokaliseret på højderyggen. Også de undersøgte forekomster ved Øresund og Skåne menes i det store og hele at repræsentere omlejrede sedimenter, måske stammende fra et dengang sedimentdækket område af Fennoscandia. Ifølge de få foreliggende tungmineralanalyser af bornholmske materialer kan antages, at sedimenterne her i hvert fald til dels stammer fra et grundfjeldsområde, som sandsynligvis har ligget udenfor det nuværende Bornholm.

Bassinet og sedimentationsudviklingen

I dette afsnit søges resultaterne af undersøgelsen sammenstillet til et helhedsbillede af aflejringsforholdene i området i rhætisk, jurassisk og nedre kretacisk tid. Til støtte for denne redegørelse er de palæogeografiske kortskitser fig. 44–48 udarbejdet; disse kort viser også hovedtræk af tungmineralsammensætningen.

Her skal der først erindres om, at det Danske Sænkningsområde indgår som en del af det nordeuropæiske aflejringsfelt, som siden sen-palæozoisk tid har indtaget området mellem groft sagt Fennoscandia i nord og de Variskiske bjerge i syd. Ved sin hovedudstrækning i nordvestlig-sydøstlig retning føjer det Danske Sænkningsområde sig ind som et naturligt led i det strukturmønster, som spores i de tilstødende dele af bassinet, især Nordtyskland og Polen (sml. f. eks. KÖLBEL, 1957). – Betragtes det nordeuropæiske aflejringsfelt må skønnes, at de til dette hørende denudationsområder i alt væsentligt har været Fennoscandia og de Variskiske bjergkæderester; flere træk i mineralsammensætningen i trias, jura og nedre kridt i Nordvesttyskland (bl. a. WURSTER, 1964; v. ENGELHARDT, 1942; DEECKE, 1935) tyder på, at en materialtilførsel fra nord eller nordøst har gjort sig ret stærkt gældende; som tidligere nævnt anses lignende forhold at have været fremherskende i det Danske Sænkningsområde.

Af fig. 3 (p. 22) ses bl. a., at sedimentakkumulationen ikke har været lige stor overalt i det undersøgte område. Størst mægtighed findes ved Fjerritslev i Nordjylland (linie A, fig. 3). Længere mod øst (linie C, fig. 3) er den lokalt største jura-lagtykkelse truffet ved Øresund. På Bornholm er der omkring 750 m jura (GRY, 1960). Disse tre lokaliteter med stor sedimenttykkelse falder i et NV-SØ orienteret strøg, som indtil videre antages at repræsentere en tektonisk anlagt sænkningszone; den ses f. eks. aftegnet på de palæogeografiske kort ved at den øjensynlig ikke påvirkes af den tillanding, som iøvrigt prægede den sydlige del af det Danske Sænkningsområde i mellem og øvre jura. I nedre kridt synes forholdet at have været et andet, idet dele af det skånske afsnit af „zonen" ikke længere fremtræder som aflejringsområde (fig. 48); bl. a. under henvisning til Øresundsundersøgelsens resultater (LARSEN et al., 1965; LARSEN, 1966) menes dette at hænge sammen med en strukturændring, hvorved den Fennoscandiske Randzone, i stort set den skikkelse vi kender den i dag, er opstået. – Foruden disse større træk i aflejringsområdets udformning er der også stedvis udviklet en lokal-topografi i bassinbunden; her er der utvivlsomt tale om et udslag af salttektonik.

Sedimentationsudviklingen og de palæogeografiske forhold i området kan kort skitseres således:

Ved begyndelsen af rhætisk tid (fig. 44) var det Danske Sænkningsområde sandsynligvis til dels havdækket. Dette fremgår tydeligst i den vestlige del (Vinding), men også andre steder er der tegn på marine forhold. Nogle steder langs bassinranden skete der samtidig en udbygning af sandede deltaformationer. Det største delta („Gassum deltaet") fandtes ved kysten mod det Fennoscandiske landområde; her har der formentlig været udmunding for flere større flodløb, i hvis dræningsområde især grundfjeldskomplexer har været exponeret. Ringkøbing-Fyn Højderyggen har formentlig ligget hen som en ø, ved hvis kyst et andet, mindre delta („Ullerslev deltaet") var lokaliseret; på denne ø har formentlig væsentligst ældre sedimentformationer været blotlagt.

I nedre jura (fig. 45) skete der en transgression, således at de rhætiske deltadannelser praktisk taget helt oversvømmedes af havet. Herved aflejredes fortrinsvis mørktfarvede, lerede sedimenter. Materialtilførslen til bassinet er sandsynligvis foregået fra samme denudationsfelter og ad samme flodsystemer som i rhæt. Havstigningen har formentlig påvirket disse flodløbs erosionsbasis, således at der er sket en betydelig sedimentation i flodlejerne.

Mellem jura (fig. 46) er først og fremmest karakteriseret ved en regression. I tilknytning hertil skete der dels en tillanding af den sydligere del af det Danske Sænkningsområde og dels en kraftig deltaudbygning („Haldager deltaet") ved randen af Fennoscandia; det er formentlig til dels forvitrede, omlejrede materialer fra de nedre jurassiske flodsengssedimenter, der indgår heri.

I øvre jura (fig. 47) skete der øjensynlig en yderligere indsnævring af aflejringsområdet til trods for, at der samtidig foregik en transgression; transgressionen medførte, at det mellem jurassiske delta blev tildækket af marine leraflejringer. Vestligt i området vedvarede lersedimentationen gennem hele øvre jura, medens den afløstes af en marin sandsedimentation langs kysten mod Fennoscandia; sandmaterialerne er formentlig tilført fluviatilt til dels fra Fennoscandiske grundfjeldsområder.

I den vestlige del af aflejringsområdet fortsatte den marine lersedimentation øjensynlig uændret ved overgangen til nedre kridt (fig. 48); andre steder indtraf der derimod betydelige ændringer, nemlig dels en transgression ind over de sydligere dele af det Danske Sænkningsområde og dels en regression langs randen af Fennoscandia. Disse ændringer i de palæogeografiske forhold skal muligvis ses i sammenhæng med dannelsen af den Fennoscandiske Randzone. Regressionen gav sig bl. a. til kende ved dannelsen af „wealden facies" i form af deltaformationer langs kysten mod Fennoscandia. I løbet af nedre kridt er der øjensynlig foregået flere mindre oscillationer i havets udbredelse. Ved slutningen, i albien, indtraf en omfattende transgression, hvorunder også Ringkøbing-Fyn Højderyggen blev havdækket; med albien-transgressionen fulgte tillige en ændring fra terrigen sedimentation til kalksedimentation; denne ændring slog dog ikke igennem langs den Fennoscandiske kystzone, formentlig fordi der her stadigvæk foregik en betydelig fluviatil materialtilførsel.

Denne albien-transgression betegner i virkeligheden afslutningen på den udvikling, som siden rhæt havde præget det Danske Sænkningsområde, og samtidig indledningsfasen til en ny sedimentologisk-palæogeografisk situation, som kom til at gøre sig gældende i området i hele øvre kridt.

Afsluttende bemærkninger

Ved den her refererede undersøgelse er nogle træk af sedimentationshistorien i det Danske Sænkningsområde i rhætisk, jurassisk og nedre kretacisk tid søgt belyst; adskillige forhold er dog endnu ganske uopklarede. Dette hænger sammen med, at undersøgelsen indenfor de afstukne rammer ikke har kunnet behandle alle sider af sedimentmaterialets beskaffenhed. Ved fremtidige undersøgelser af andre sedimentkarakterer må det være muligt af føje væsentlige træk til det billede af sedimentationsudviklingen, som har kunnet opridses her.

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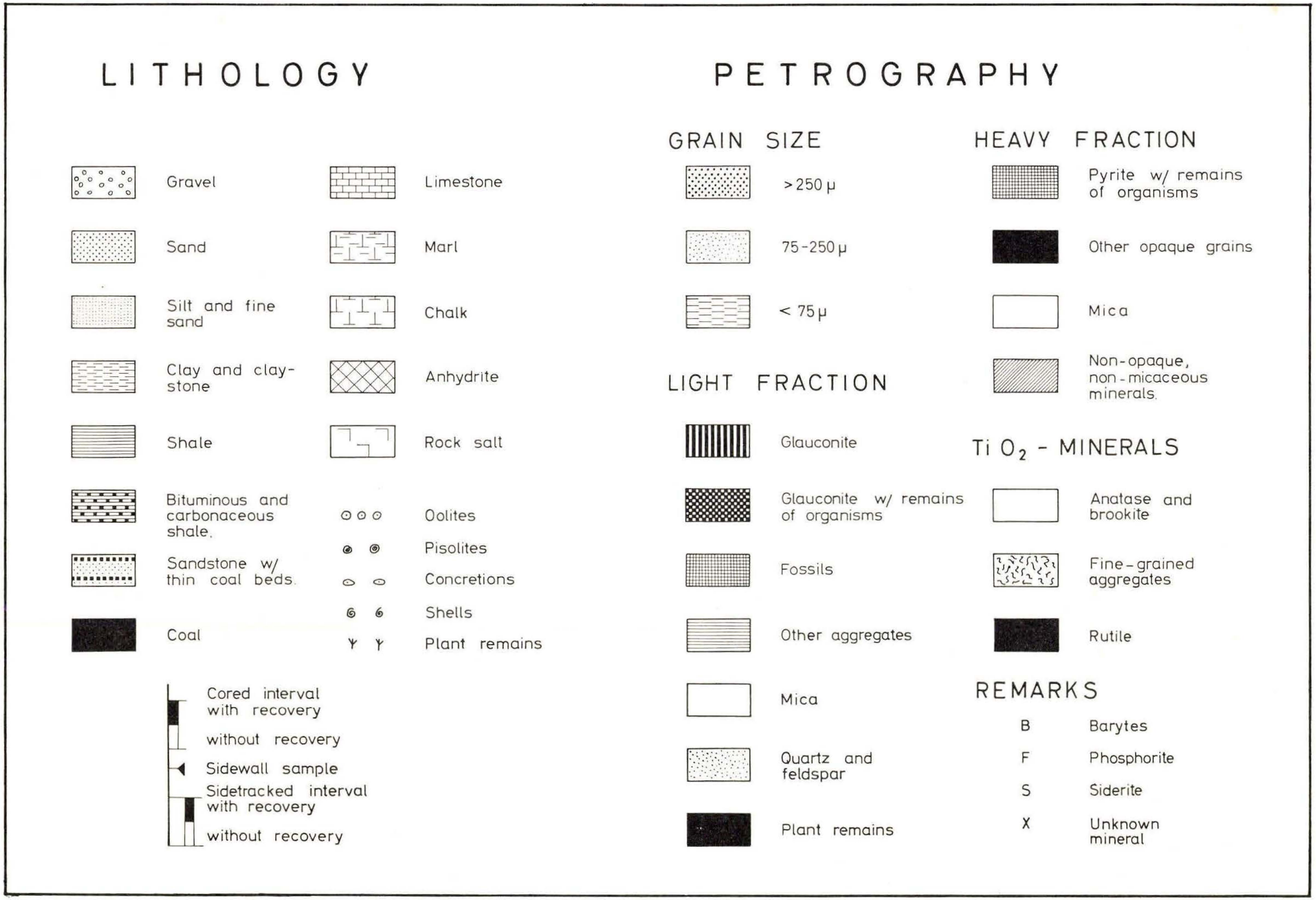
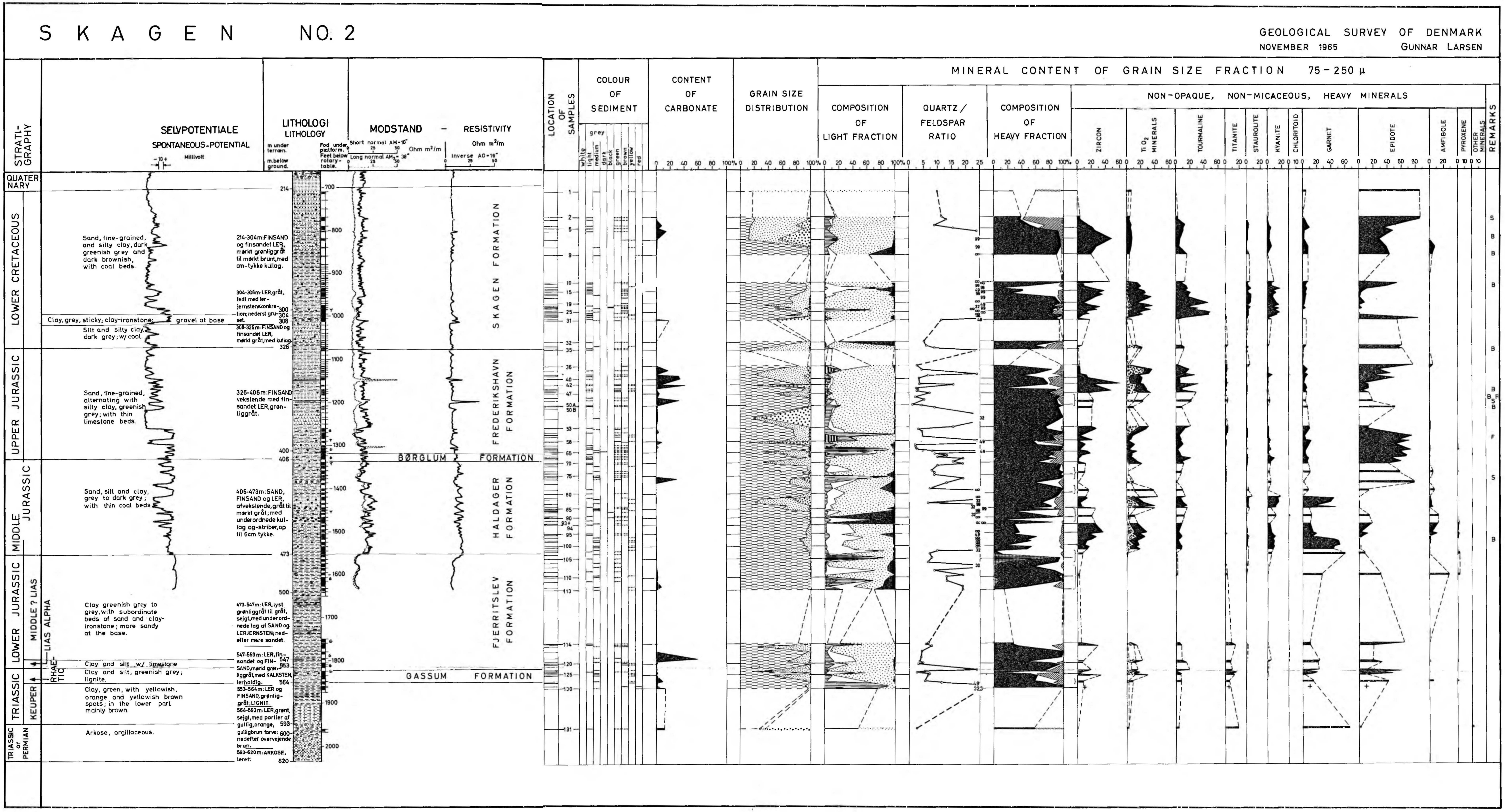
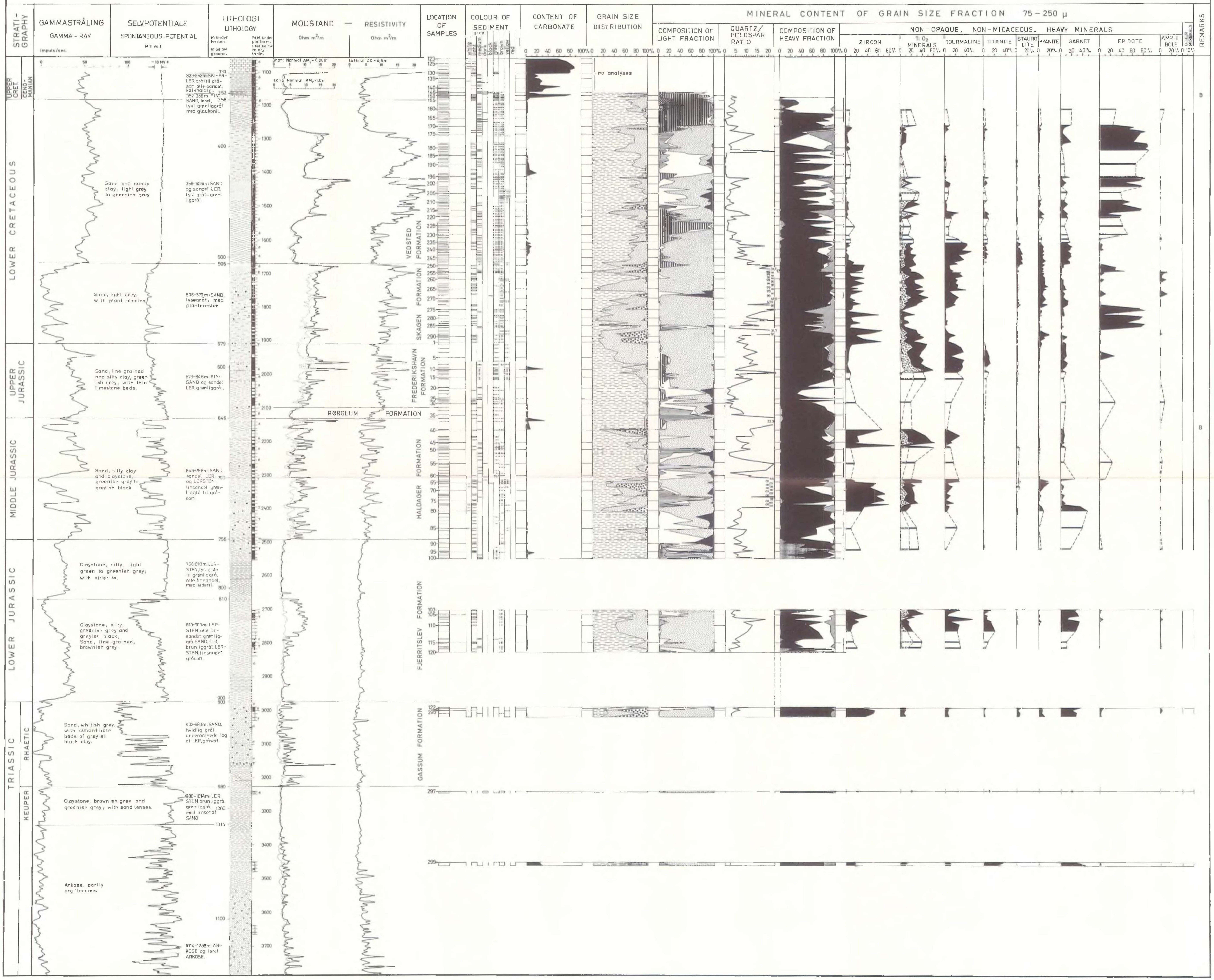
LIST OF PLATES


LITHOLOGY
Gravel
Sand
Silt and fine sand
Clay and clay-stone
Shale
Bituminous and carbonaceous shale.
Sandstone w/ thin coal beds.
Coal
Limestone
Marl
Chalk
Anhydrite
Rock salt
Oolites
Pisolites
Concretions
Shells
Plant remains
Cored interval with recovery
without recovery
Sidewall sample
Sidetracked interval with recovery
without recovery
PETROGRAPHY
GRAIN SIZE
>250 μ
75-250 μ
< 75 μ
LIGHT FRACTION
Glauconite
Glauconite w/ remains of organisms
Fossils
Other aggregates
Mica
Quartz and feldspar
Plant remains
HEAVY FRACTION
Pyrite w/ remains of organisms
Other opaque grains
Mica
Non-opaque, non-micaceous minerals.
Ti O2 - MINERALS
Anatase and brookite
Fine-grained aggregates
Rutile
REMARKS
B Barytes
F Phosphorite
S Siderite
X Unknown mineral


SKAGEN NO. 2
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m under terræn.
m.below ground.
Fod under platform.
Feet below rotary-table.
MODSTAND - RESISTIVITY
Short normal AM-10"
Long normal AM-38"
Ohm m²/m
Inverse AO-16"
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
white
light
medium
dark
black
green
brown
yellow
red
grey
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 - 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO2 MINERALS
TOURMALINE
TITANITE
STAUROLITE
KYANITE
CHLORITOID
GARNET
EPIDOTE
AMFIBOLE
PYROXENE
OTHER MINERALS
REMARKS
QUATERNARY
LOWER CRETACEOUS
UPPER JURASSIC
MIDDLE JURASSIC
LOWER JURASSIC
MIDDLE ? LIAS
LIAS ALPHA
RHAETIC
TRIASSIC
KEUPER
TRIASSIC or PERMIAN
Sand, fine-grained, and silty clay, dark greenish grey and dark brownish, with coal beds.
Clay, grey, sticky; clay-ironstone; gravel at base
Silt and silty clay, dark grey; w/ coal.
Sand, fine-grained, alternating with silty clay, greenish grey; with thin limestone beds.
Sand, silt and clay, grey to dark grey; with thin coal beds.
Clay greenish grey to grey, with subordinate beds of sand and clay-ironstone; more sandy at the base.
Clay and silt w/ limestone
Clay and silt, greenish grey; lignite.
Clay, green, with yellowish, orange and yellowish brown spots; in the lower part mainly brown.
Arkose, argillaceous.
214-304m: FINSAND og finsandet LER, mørkt grønliggråt til mørkt brunt, med cm-tykke kullag.
304-308m: LER, gråt, fedt med ler-jernstenskonkretion; nederst gruset.
308-326m: FINSAND og finsandet LER, mørkt gråt, med kullag.
326-406m: FINSAND vekslende med finsandet LER, grønliggråt.
406-473m: SAND, FINSAND og LER, afvekslende, gråt til mørkt gråt; med underordnede kullag og -striber, op til 6cm tykke.
473-547m: LER, lyst grønliggråt til gråt, sejgt, med underordnede lag af SAND og LERJERNSTEN; nedefter mere sandet.
547-553m: LER, finsandet og FINSAND, mørkt grønliggråt, med KALKSTEN, lerholdig.
553-564m: LER og FINSAND, grønliggråt; LIGNIT.
564-593m: LER, grønt, sejgt, med partier af gullig, orange, gulligbrun farve; nedefter overvejende brun.
593-620m: ARKOSE, leret.
SKAGEN FORMATION
FREDERIKSHAVN FORMATION
BØRGLUM FORMATION
HALDAGER FORMATION
FJERRITSLEV FORMATION
GASSUM FORMATION

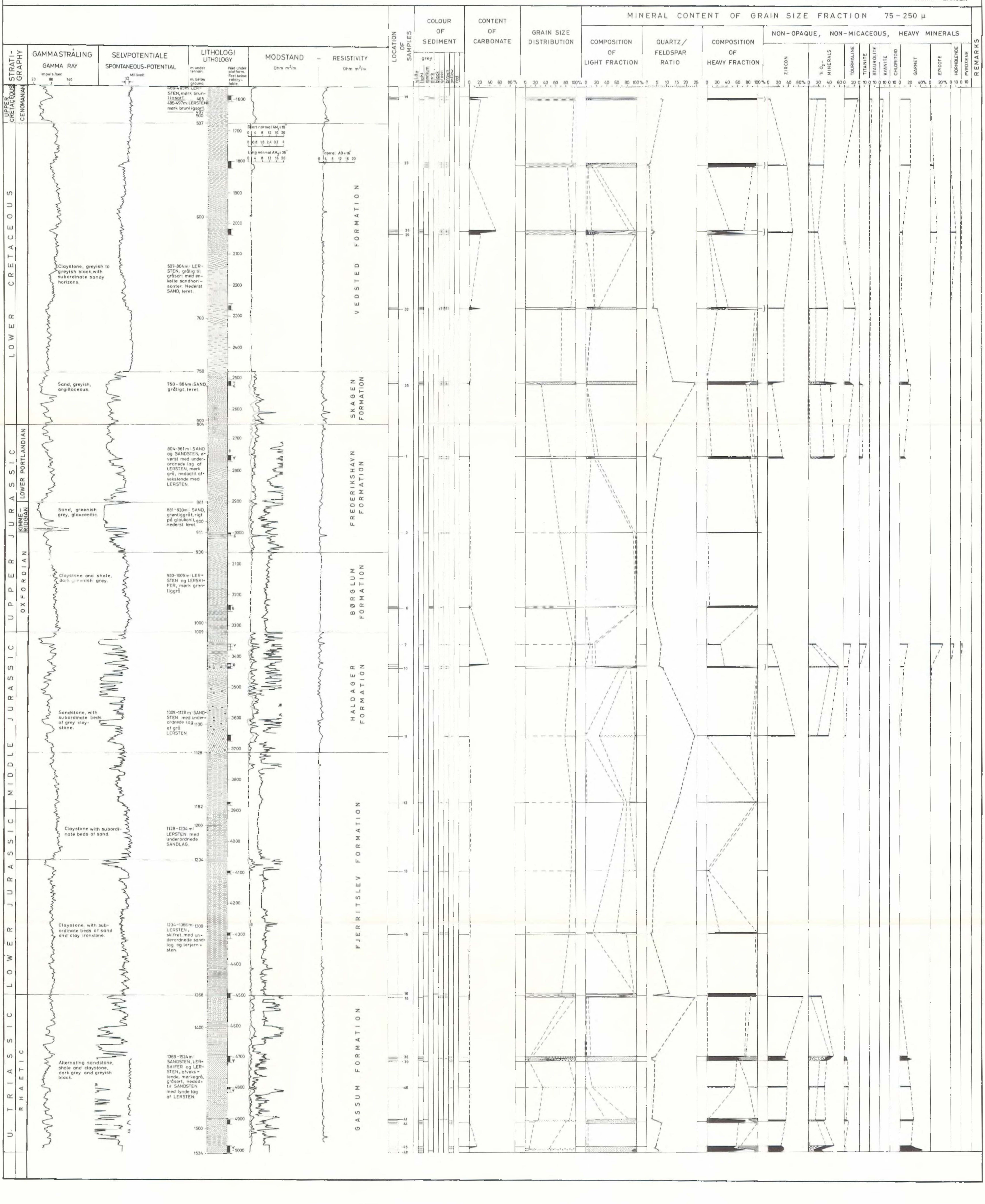
FREDERIKSHAVN CITY NO. 1

GEOLOGICAL SURVEY OF DENMARK
OCTOBER 1965 GUNNAR LARSEN

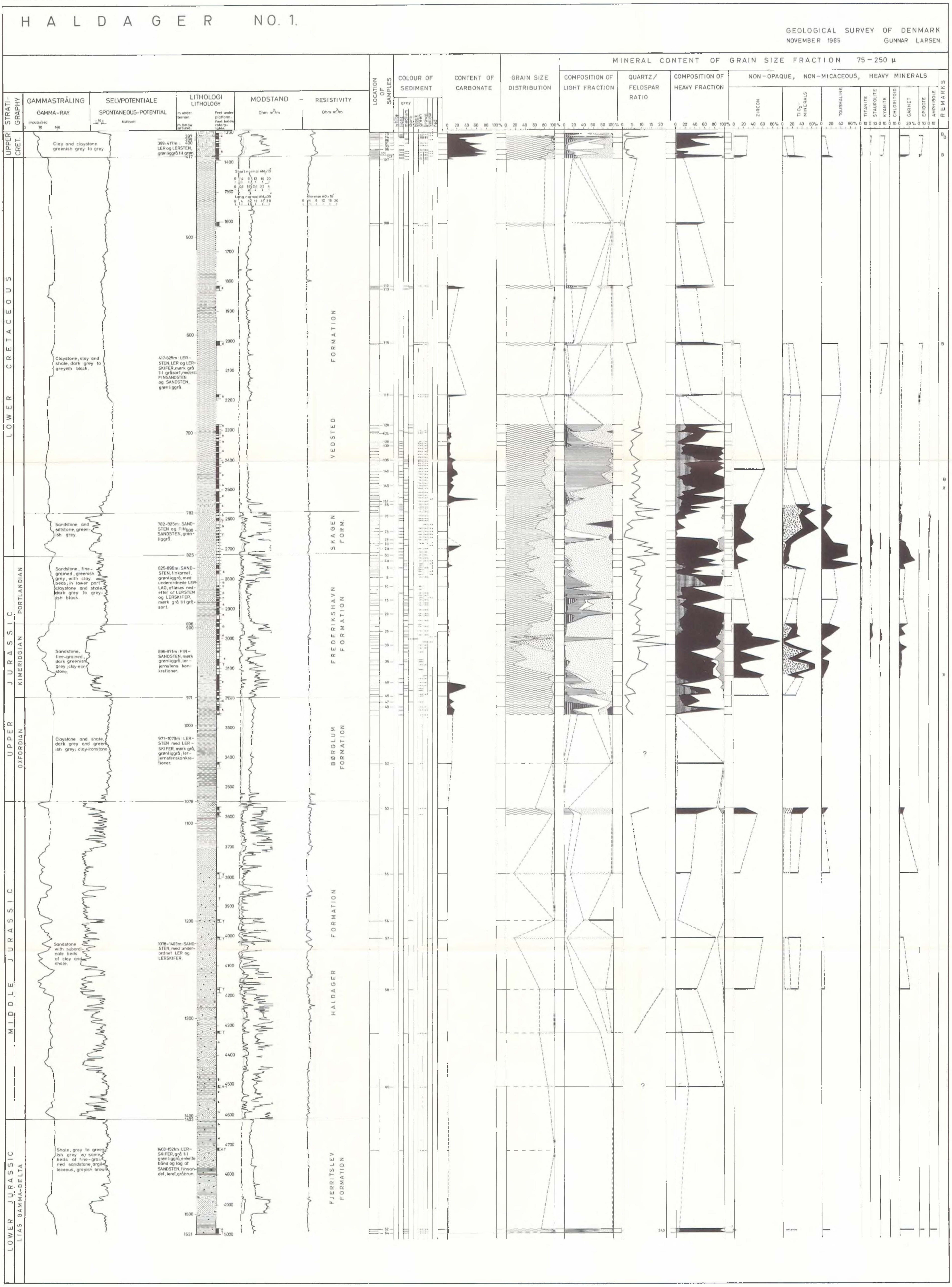


B Ø R G L U M NO. 1

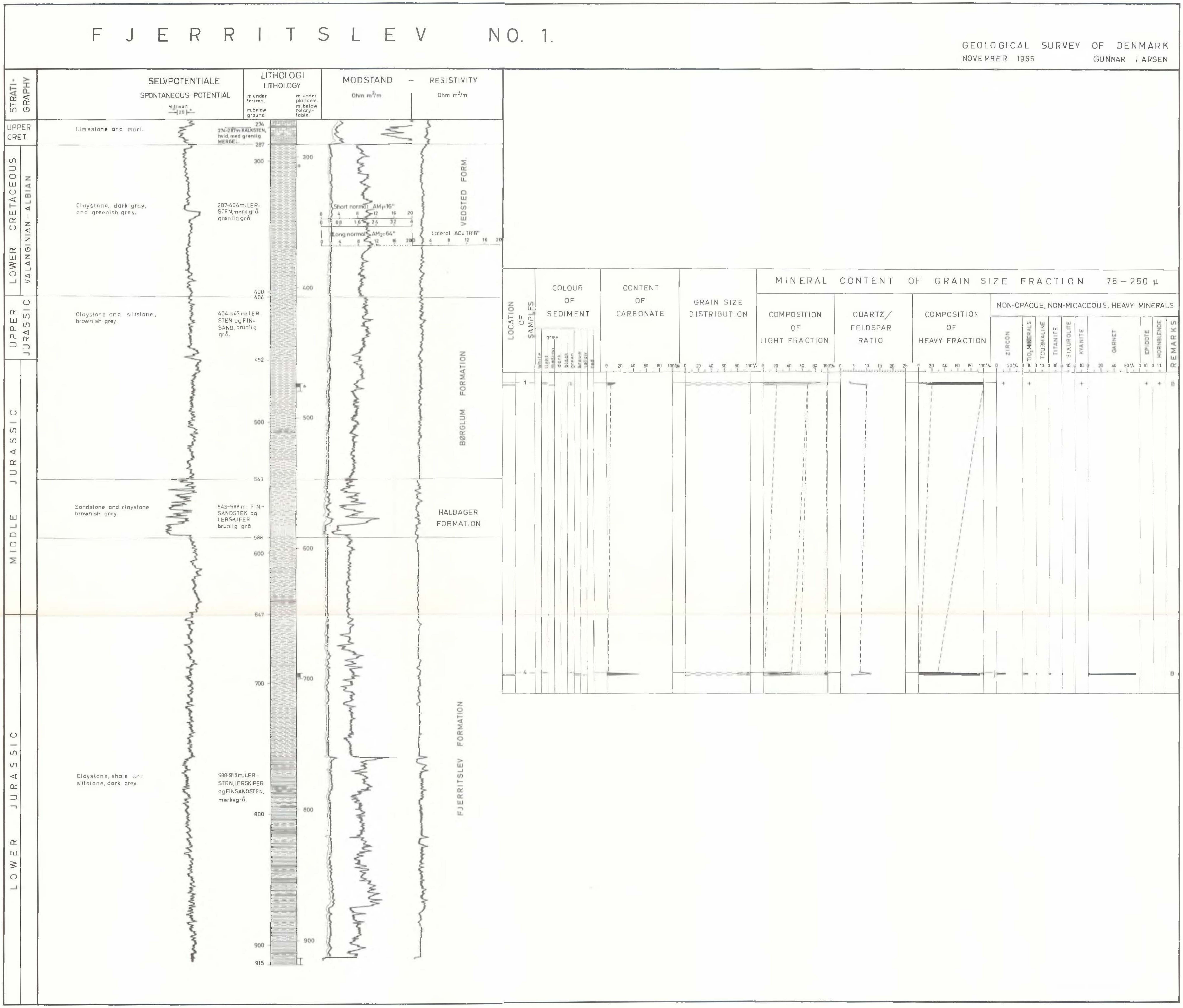
GEOLOGICAL SURVEY OF DENMARK
DECEMBER 1965 GUNNER LARSEN



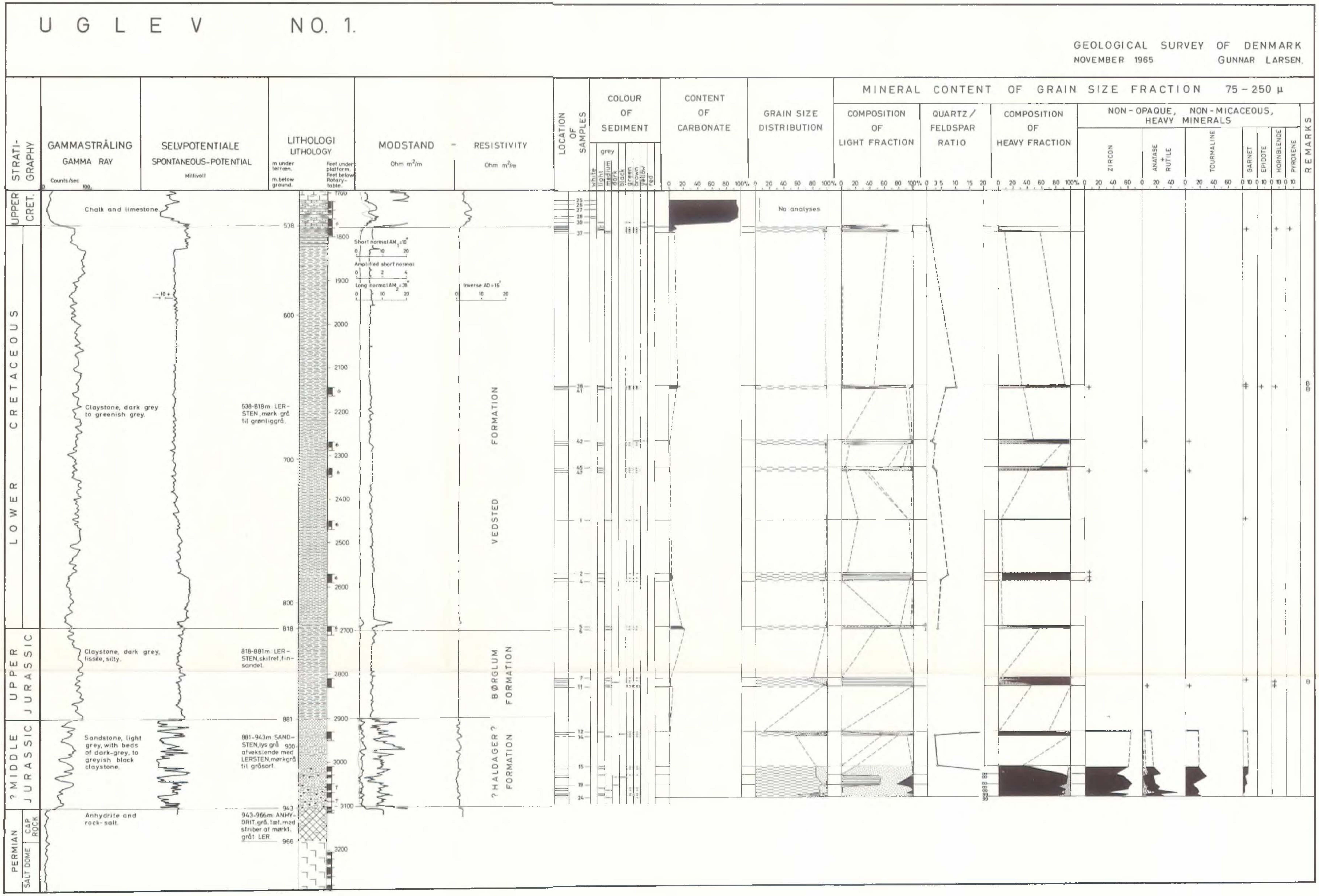
FLYVBJERG NO. 1
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965 GUNNAR LARSEN
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
LITHOLOGI
LITHOLOGY
MODSTAND - RESISTIVITY
LOWER CRETACEOUS
UPPER JURASSIC
MIDDLE JURASSIC
LOWER JURASSIC
UPPER TRIASSIC
RHAETIC
KEUPER
Shale and clay, greyish black.
520-750 m: LERSKIFER og LER, mørkt gråsort.
Sand, white, mainly fine-grained.
750-777 m: SAND, hvidt, overvejende fin- til mellemkornet.
Sand, fine-grained white, glauconitic, micaceous.
777-885 m: SAND, hvidt finkornet glaukonitisk, glimmerholdigt.
Clay and shale, silty, greyish green.
885-950 m: LER og LERSKIFER, grågrønt, finsandet.
Sand and sandstone, greenish white, w/ silt and shale, greenish grey.
950-1060 m: SAND og SANDSTEN, grønlighvid, m. FINSAND og SKIFERLER, grønliggråt.
Shale, green to greenish grey
1060-1149 m: LERSKIFER, grønlig til grønliggråt, med grønliggråt, finsandet SKIFERLER.
Shale, light greenish grey, and sand, greyish white.
1149-1306 m: LERSKIFER og SKIFERLER, lys grønliggråt, og gråhvidt SAND.
Sand, greenish white, sandstone, brownish white, and shale, dark grey.
1306-1480 m: SAND, grønlighvidt, SANDSTEN, brunlighvid, LERSKIFER, mørkegrå.
Claystone, green and reddish brown; sandstone, coarse-grained whitish grey.
1480-1695 m: LERSTEN, grøn og rødligbrun; SANDSTEN, grov, hvidlig grå.
VEDSTED FORMATION
SKAGEN FORMATION
FREDERIKSHAVN FORMATION
BØRGLUM FORMATION
HALDAGER FORMATION
FJERRITSLEV FORMATION
GASSUM FORMATION
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75-250 μ
COMPOSITION OF LIGHT FRACTION
QUARTZ/FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TOURMALINE
TITANITE
STAUROLITE
KYANITE
CHLORITOID
GARNET
EPIDOTE
HORNBLENDE
PYROXENE
REMARKS


HALDAGER NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965 GUNNAR LARSEN.
STRATIGRAPHY
GAMMASTRÅLING
GAMMA-RAY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
LITHOLOGI
LITHOLOGY
MODSTAND - RESISTIVITY
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 μ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO2-MINERALS
TOURMALINE
TITANITE
STAUROLITE
KYANITE
CHLORITOID
GARNET
EPIDOTE
AMPHIBOLE
REMARKS
UPPER CRET.
LOWER CRETACEOUS
UPPER JURASSIC
PORTLANDIAN
KIMERIDGIAN
OXFORDIAN
MIDDLE JURASSIC
LOWER JURASSIC
LIAS GAMMA-DELTA
Clay and claystone greenish grey to grey.
399-417m: LER og LERSTEN, grønliggrå til grøn
Claystone, clay and shale, dark grey to greyish black.
417-825m: LER-STEN, LER og LER-SKIFER, mørk grå til gråsort, nederst FINSANDSTEN og SANDSTEN, grønliggrå.
Sandstone and siltstone, greenish grey.
782-825m: SANDSTEN og FINSANDSTEN, grønliggrå.
Sandstone, fine-grained, greenish grey, with clay beds; in lower part claystone and shale, dark grey to greyish black.
825-896m: SANDSTEN, finkornet, grønliggrå, med underordnede LERLAG, afløses nedefter af LERSTEN og LERSKIFER, mørk grå til gråsort.
Sandstone, fine-grained, dark greenish grey; clay-ironstone.
896-971m: FINSANDSTEN, mørk grønliggrå, lerjernstens konkretioner.
Claystone and shale, dark grey and greenish grey; clay-ironstone.
971-1078m: LERSTEN med LERSKIFER, mørk grå, grønliggrå, lerjernstenskonkretioner.
Sandstone with subordinate beds of clay and shale.
1078-1403m: SANDSTEN, med underordnet LER og LERSKIFER.
Shale, grey to greenish grey w/ some beds of fine-grained sandstone, argillaceous, greyish brown.
1403-1521m: LERSKIFER, grå til grønliggrå, enkelte bånd og lag af SANDSTEN, finsandet, leret, gråbrun.
VEDSTED FORMATION
SKAGEN FORM.
FREDERIKSHAVN FORMATION
BØRGLUM FORMATION
HALDAGER FORMATION
FJERRITSLEV FORMATION

VEDSTED NO. 1
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m. under terræn
m. below ground
m. under platform
m. below Rotary-table
MODSTAND - RESISTIVITY
Ohm m²/m
Short normal
Long normal
Inverse
UPPER CRET.
CENOMANIAN
Marl and shale
430 - 457 m: MERGEL, hvidliggrøn til grøn, med spor af LERSKIFER, mørkegrå
APTIAN - ALBIAN
Claystone, soft, dark grey, silty; shale, dark grey, silty, glauconitic slightly micaceous
457 - 626 m: LERSTEN, blød, mørkegrå, finsandet, og LERSKIFER, mørkegrå, stærkt finsandet, glaukonitisk, let glimmerholdig.
LOWER CRETACEOUS
BARREMIAN
Claystone, dark grey, soft, silty.
626 - 710 m: LERSTEN, mørkegrå, blød, finsandet.
HAUTERIVIAN
Claystone, dark grey, soft, slightly silty.
710 - 843 m: LERSTEN, mørkegrå, blød, let finsandet.
VALANGINIAN
Claystone, dark grey, soft, w/ some shale, dark grey.
843 - 975 m: LERSTEN, mørkegrå, blød, med nogen LERSKIFER mørkegrå.
UPPER JURASSIC
Siltstone, argillaceous, greenish grey
975 - 1018 m FINSANDSTEN, leret grøngrå.
Claystone, silty greenish grey
1018 - 1120 m LERSTEN, finsandet, grøngrå.
MIDDLE JURASSIC
Sandstone, grey and yellowish brown.
1120 - 1220 m SANDSTEN, grå og gulligbrun.
LOWER JURASSIC
Shale, grey to dark grey, occasionally with fine-grained sand, with siderite locally.
1220 - 1899 m: LERSKIFER, grå, mørkegrå, lejlighedsvis spor af FINSANDSTEN, hvid, lokalt med siderit.
U. TRIASSIC
RHAETIC
Siltstone and sandstone, white, with thin beds of grey shale and coal
1899 - 2065 m: FINSANDSTEN, hvid og LERSKIFER, grå; tyndt mellemlejret og krydslejret SANDSTEN, hvid, med kullag.
VEDSTED FORMATION
FREDERIKSHAVN FORM.
BØRGLUM FORMATION
HALDAGER FORMATION
FJERRITSLEV FORMATION
GASSUM FORMATION
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 μ
COMPOSITION OF LIGHT FRACTION
QUARTZ/FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO₂-MINERALS
TOURMALINE
TITANITE
STAUROLITE
GARNET
EPIDOTE
HORNBLENDE
REMARKS

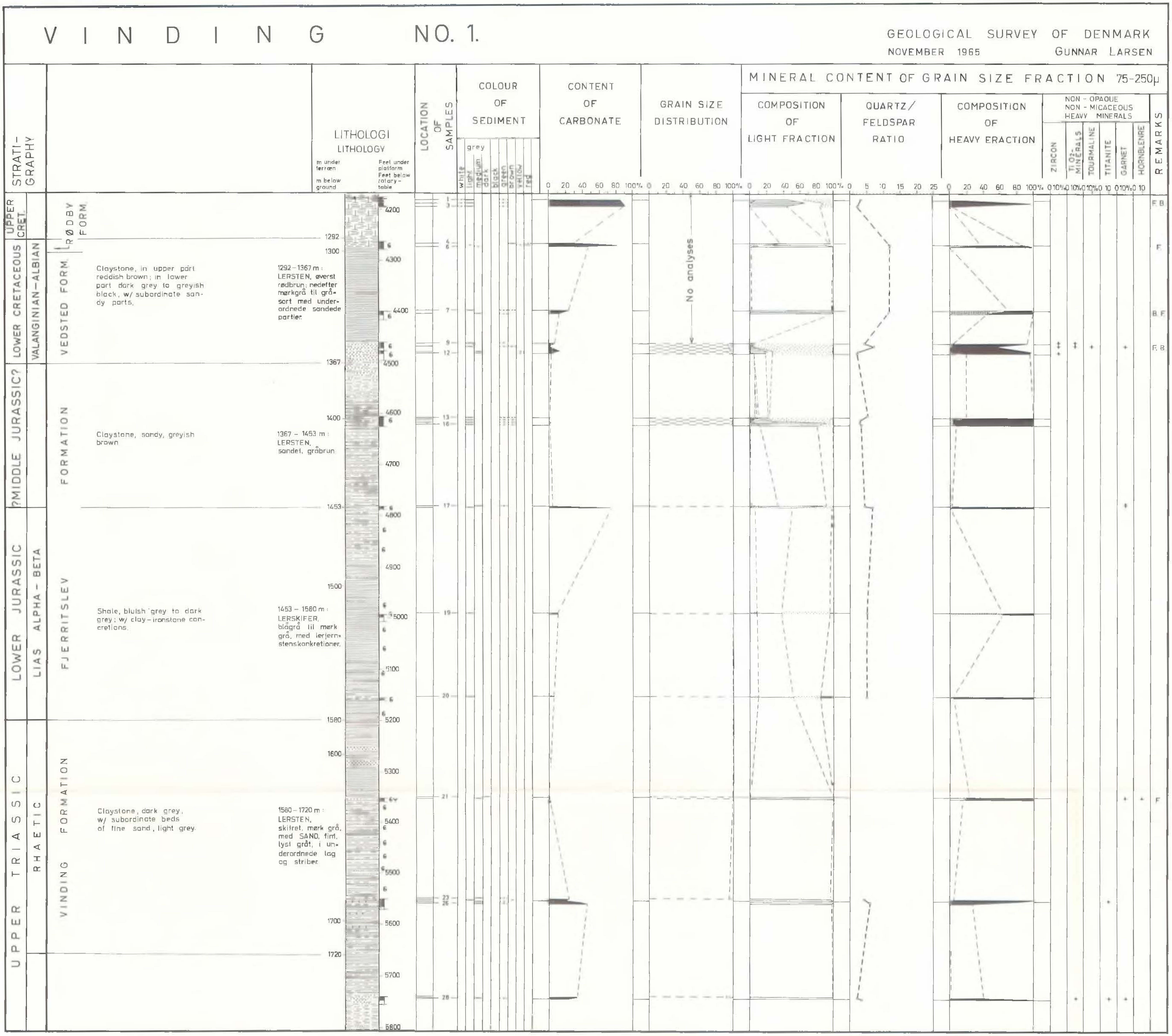

F J E R R I T S L E V NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN
STRATI-GRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt 20
LITHOLOGI
LITHOLOGY
m under terræn.
m.below ground.
m under platform.
m.below rotary-table.
MODSTAND – RESISTIVITY
Ohm m²/m
Ohm m²/m
UPPER CRET.
Limestone and marl.
274-287m KALKSTEN, hvid, med grønlig MERGEL.
LOWER CRETACEOUS
VALANGINIAN - ALBIAN
Claystone, dark grey, and greenish grey.
287-404m: LER-STEN, mørk grå, grønlig grå.
Short normal AM₁=16"
Long normal AM₂=64"
Lateral AO=18'8"
VEDSTED FORM.
UPPER JURASSIC
Claystone and siltstone, brownish grey.
404-543m: LER-STEN og FIN-SAND, brunlig grå.
BØRGLUM FORMATION
MIDDLE JURASSIC
Sandstone and claystone brownish grey
543-588 m: FIN-SANDSTEN og LERSKIFER brunlig grå.
HALDAGER FORMATION
LOWER JURASSIC
Claystone, shale and siltstone, dark grey
588-915m: LER-STEN, LERSKIFER og FINSANDSTEN, mørkegrå.
FJERRITSLEV FORMATION
274
287
300
400
404
452
500
543
588
600
647
700
800
900
915
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
grey
white
light
medium
dark
black
green
brown
yellow
red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO₂ MINERALS
TOURMALINE
TITANITE
STAUROLITE
KYANITE
GARNET
EPIDOTE
HORNBLENDE
REMARKS
1
4
B

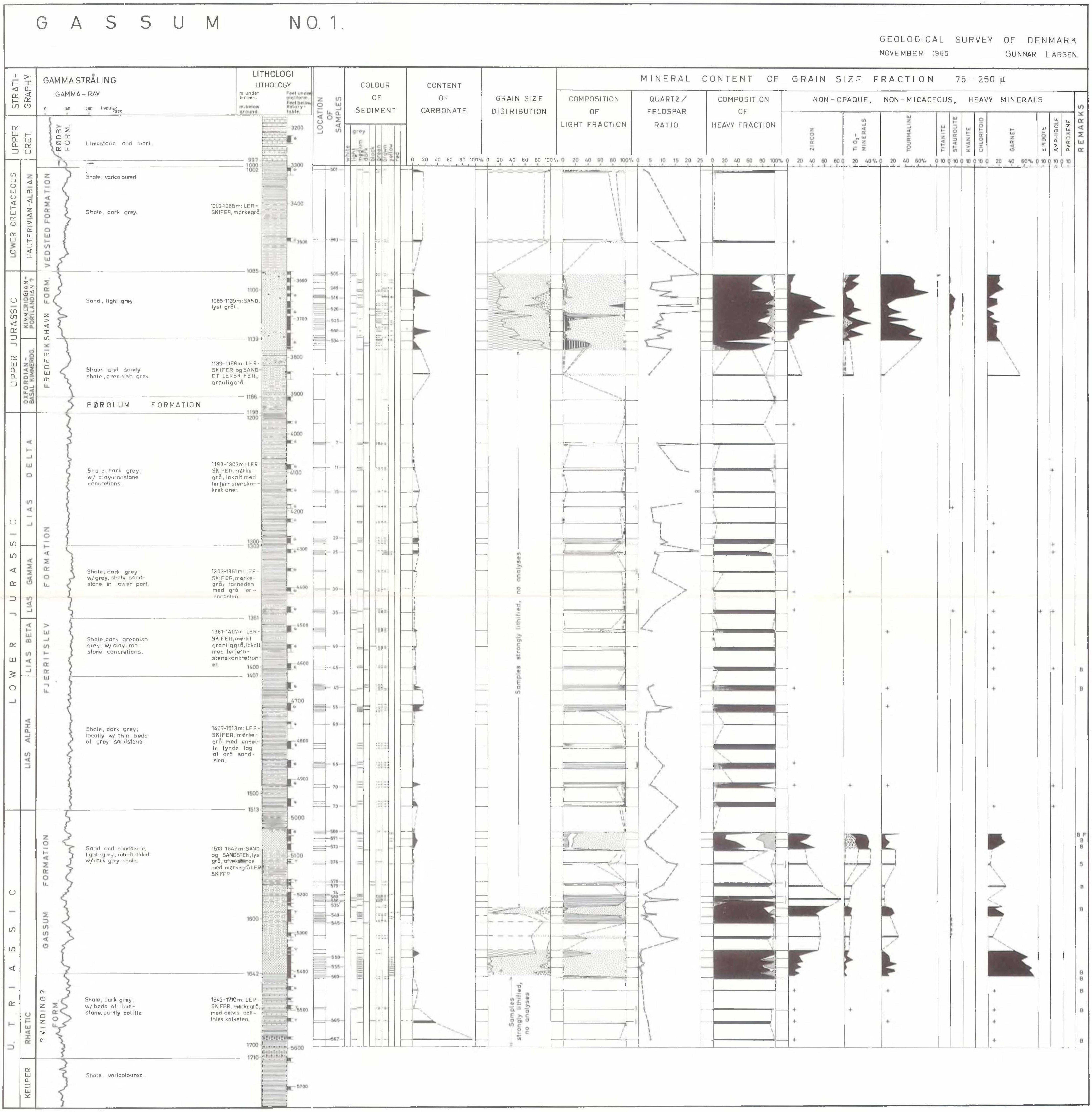

F J E R R I T S L E V NO. 2
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
G. LARSEN
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m under terræn. m. below ground.
m under platform. m. below rotary-table.
MODSTAND – RESISTIVITY
Ohm m²/m
Short normal AM₁ = 16"
Long normal AM₂ = 64"
Lateral AO = 18'8"
UPPER CRET.
LOWER CRETACEOUS
VALANGINIAN — ALBIAN
UPPER JURASSIC
MIDDLE JURASSIC
LOWER JURASSIC
U.TRIASSIC
RHAETIC
KEUPER
Marl
274–286m: KALKSTEN, hvid, stedvis let glaukonitisk.
286–299m: MERGEL, grønlig, glaukonitisk.
Claystone and clay, greenish grey and greyish black; locally with greenish siltstone and sandstone, glauconitic.
299–1074m: LERSTEN og LER, grønliggrå, sortgrå, lokalt FINSAND, grønt, glimmerholdigt og SANDSTEN, grøn, glaukonitrig.
Clay and claystone, silty dark greenish grey.
1074–1260m: LERSTEN og LER, mørk grønliggrå, meget finsandet.
Sandstone, whitish grey, w/ clay beds.
1260–1320m: SANDSTEN, hvidliggrå, med lerlag
Shale, dark grey, with beds of sandstone, fine-grained, whitish grey, glauconitic
1320–1539m: LERSKIFER, mørkegrå, med lag af SANDSTEN, hvidliggrå, glaukonitisk, finkornet.
Shale, grey, dark grey and greenish grey; w/ siderite and in lower part beds of white sandstone.
1539–2300m: LERSKIFER, grå og mørkegrå til grønliggrå, med lag af SIDERIT; i nedre del med lag af hvid SANDSTEN.
Alternating thin beds of shale, dark grey, silty, and sandstone, white, slightly glauconitic; w/coal pieces
2300–2326m: Alternerende tynde lag af LERSKIFER, mørkegrå, finsandet, glimmerholdig og SANDSTEN, hvid, let glaukonitisk med kulstumper.
2326–2341m: LERSKIFER, varieret, rødligbrun og gullig-grøn.
VEDSTED FORMATION
BØRGLUM FORMATION
HALDAGER FORMATION
FJERRITSLEV FORMATION
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
grey
white light medium dark black green brown yellow red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ/ FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO₂ MINERALS
TOURMALINE
STAUROLITE
GARNET
HORNBLENDE
OTHER MINERALS
REMARKS

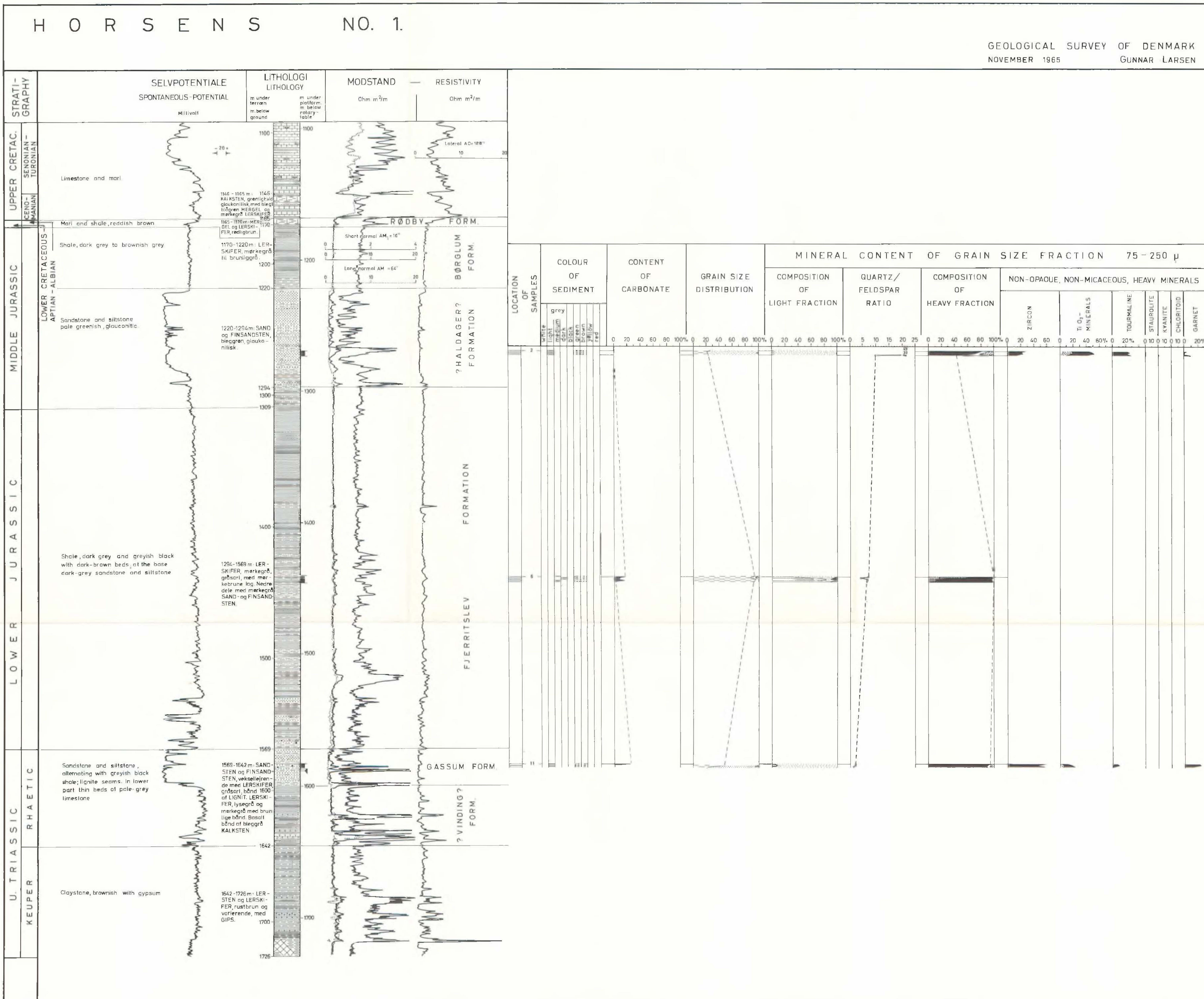


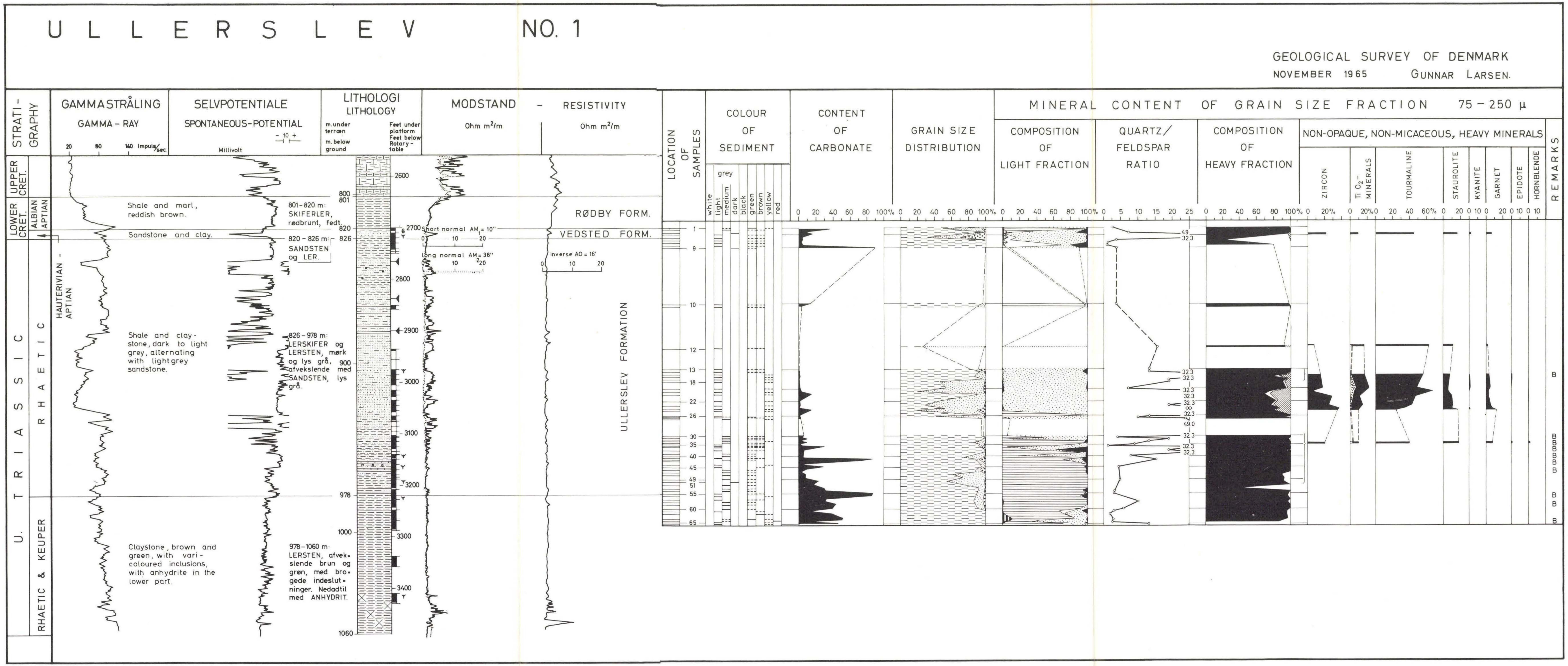
U G L E V NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN.
STRATIGRAPHY
GAMMASTRÅLING
GAMMA RAY
Counts/sec
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m under terræn.
m below ground.
Feet under platform.
Feet below Rotary-table.
MODSTAND - RESISTIVITY
Ohm m²/m
Short normal AM₁=10'
Amplified short normal
Long normal AM₂=38'
Inverse AO=16'
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
grey
white
light
medium
dark
black
green
brown
yellow
red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
ANATASE + RUTILE
TOURMALINE
GARNET
EPIDOTE
HORNBLENDE
PYROXENE
REMARKS
UPPER CRET.
LOWER CRETACEOUS
UPPER JURASSIC
? MIDDLE JURASSIC
PERMIAN
CAP ROCK
SALT DOME
Chalk and limestone.
Claystone, dark grey to greenish grey.
538-818m. LER-STEN, mørk grå til grønliggrå.
Claystone, dark grey, fissile, silty.
818-881m. LER-STEN, skifret, fin-sandet.
Sandstone, light grey, with beds of dark-grey, to greyish black claystone.
881-943m. SAND-STEN, lys grå afvekslende med LERSTEN, mørkgrå til gråsort.
Anhydrite and rock-salt.
943-966m. ANHY-DRIT, grå, tæt, med striber af mørkt, gråt LER.
538
600
700
800
818
881
900
943
966
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
VEDSTED FORMATION
BØRGLUM FORMATION
? HALDAGER FORMATION
No analyses

Plate XI

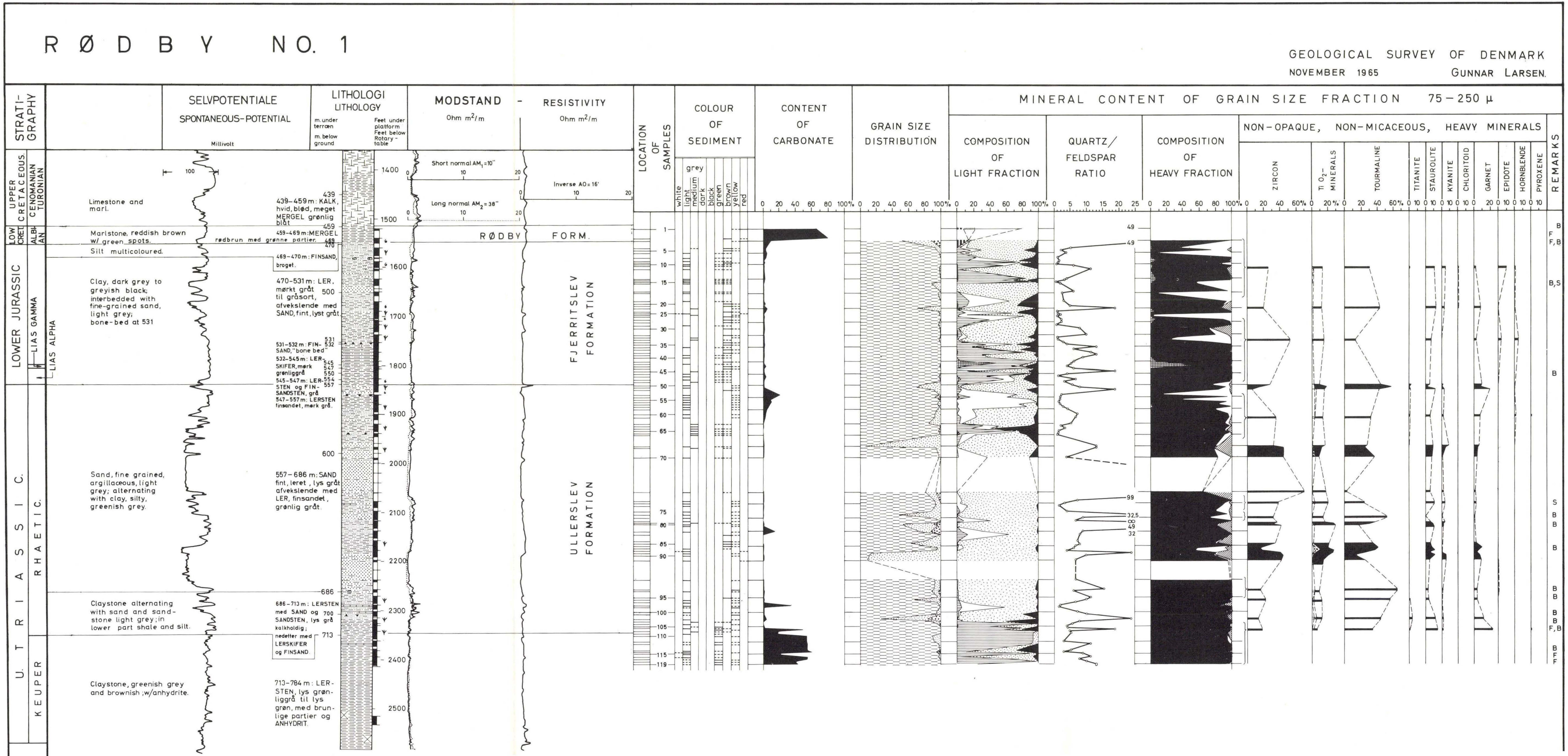

VINDING NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN
STRATI-GRAPHY
LITHOLOGI
LITHOLOGY
m under terræn
m below ground
Feet under platform
Feet below rotary-table
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
grey
white
light
medium
dark
black
green
brown
yellow
red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75-250μ
COMPOSITION OF LIGHT FRACTION
QUARTZ/FELDSPAR RATIO
COMPOSITION OF HEAVY ERACTION
NON - OPAQUE NON - MICACEOUS HEAVY MINERALS
ZIRCON
TiO2-MINERALS
TOURMALINE
TITANITE
GARNET
HORNBLENDE
REMARKS
UPPER CRET.
LOWER CRETACEOUS
VALANGINIAN-ALBIAN
?MIDDLE JURASSIC?
LOWER JURASSIC
LIAS ALPHA - BETA
UPPER TRIASSIC
RHAETIC
RØDBY FORM.
VEDSTED FORM.
FORMATION
FJERRITSLEV
VINDING FORMATION
Claystone, in upper part reddish brown; in lower part dark grey to greyish black, w/ subordinate sandy parts.
1292 – 1367 m: LERSTEN, øverst rødbrun; nedefter mørkgrå til gråsort med underordnede sandede partier.
Claystone, sandy, greyish brown
1367 – 1453 m: LERSTEN, sandet, gråbrun
Shale, bluish grey to dark grey; w/ clay-ironstone concretions.
1453 – 1580 m: LERSKIFER, blågrå til mørk grå, med lerjernstenskonkretioner.
Claystone, dark grey, w/ subordinate beds of fine sand, light grey.
1580 – 1720 m: LERSTEN, skifret, mørk grå, med SAND, fint, lyst gråt, i underordnede lag og striber.
1292
1300
1367
1400
1453
1500
1580
1600
1700
1720
4200
4300
4400
4500
4600
4700
4800
4900
5000
5100
5200
5300
5400
5500
5600
5700
5800
No analyses
F B
F
B F
F B
F

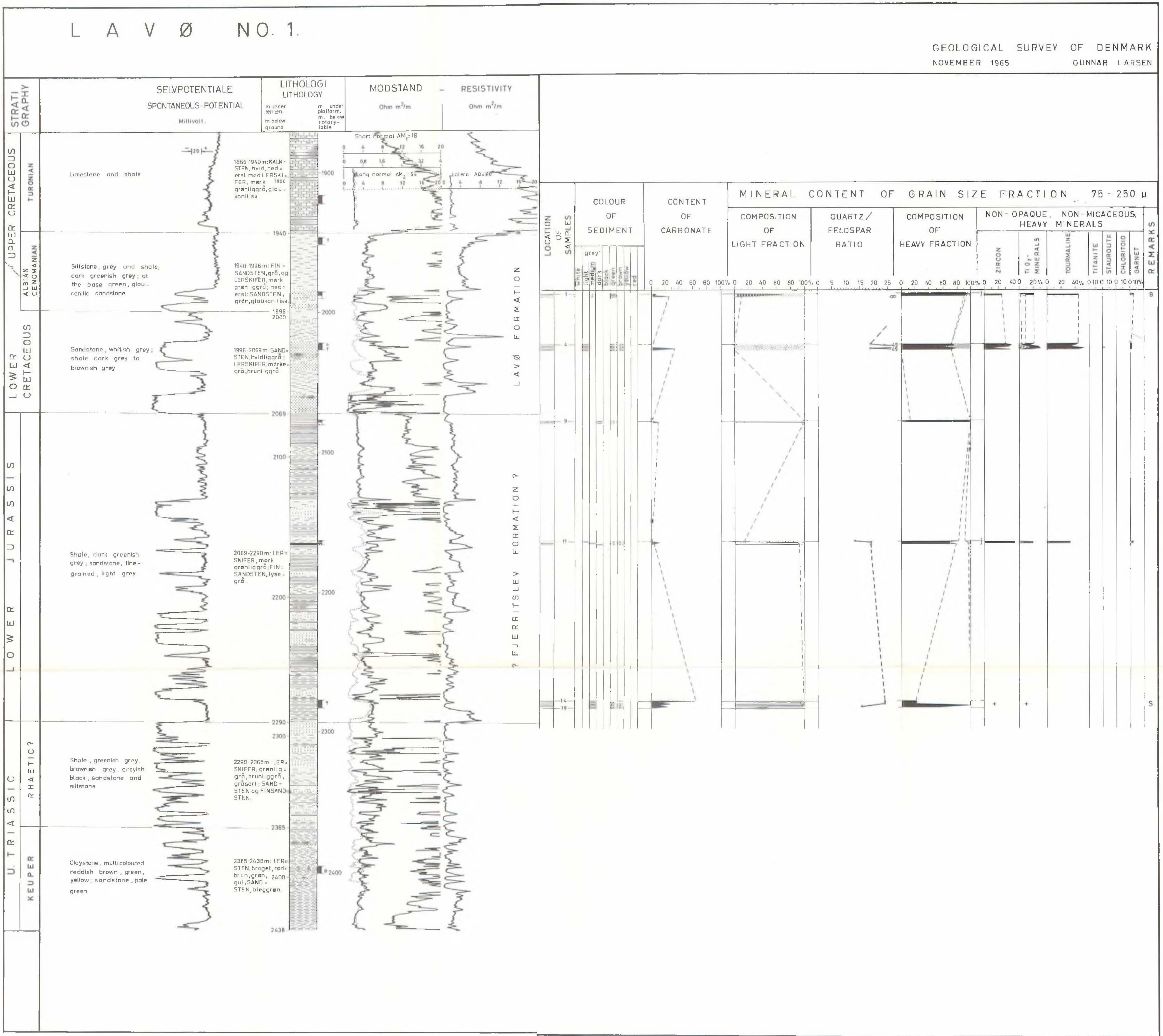

GASSUM NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN.
STRATIGRAPHY
GAMMA STRÅLING
GAMMA – RAY
LITHOLOGI
LITHOLOGY
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO2-MINERALS
TOURMALINE
TITANITE
STAUROLITE
KYANITE
CHLORITOID
GARNET
EPIDOTE
AMPHIBOLE
PYROXENE
REMARKS
UPPER CRET.
RØDBY FORM.
Limestone and marl.
LOWER CRETACEOUS
HAUTERIVIAN-ALBIAN
VEDSTED FORMATION
Shale, varicoloured
Shale, dark grey.
1002-1085 m: LERSKIFER, mørkegrå.
UPPER JURASSIC
KIMMERIDGIAN-PORTLANDIAN ?
OXFORDIAN-BASAL KIMMERIDG.
FREDERIKSHAVN FORM.
Sand, light grey.
1085-1139 m: SAND, lyst grå.
Shale and sandy shale, greenish grey.
1139-1198 m: LERSKIFER og SANDET LERSKIFER, grønliggrå.
BØRGLUM FORMATION
LOWER JURASSIC
LIAS DELTA
LIAS GAMMA
LIAS BETA
LIAS ALPHA
FJERRITSLEV FORMATION
Shale, dark grey; w/ clay-ironstone concretions.
1198-1303 m: LERSKIFER, mørkegrå, lokalt med lerjernstenskonkretioner.
Shale, dark grey; w/ grey, shaly sandstone in lower part.
1303-1361 m: LERSKIFER, mørkegrå; forneden med grå lersandsten.
Shale, dark greenish grey; w/ clay-ironstone concretions.
1361-1407 m: LERSKIFER, mørkt grønliggrå, lokalt med lerjernstenskonkretioner.
Shale, dark grey; locally w/ thin beds of grey sandstone.
1407-1513 m: LERSKIFER, mørkegrå, med enkelte tynde lag af grå sandsten.
U. TRIASSIC
GASSUM FORMATION
Sand and sandstone, light-grey, interbedded w/ dark grey shale.
1513-1642 m: SAND og SANDSTEN, lys grå, afvekslende med mørkegrå LERSKIFER
RHAETIC
? VINDING FORM.
Shale, dark grey, w/ beds of limestone, partly oolitic
1642-1710 m: LERSKIFER, mørkegrå, med delvis oolitisk kalksten.
KEUPER
Shale, varicoloured.
Samples strongly lithified, no analyses

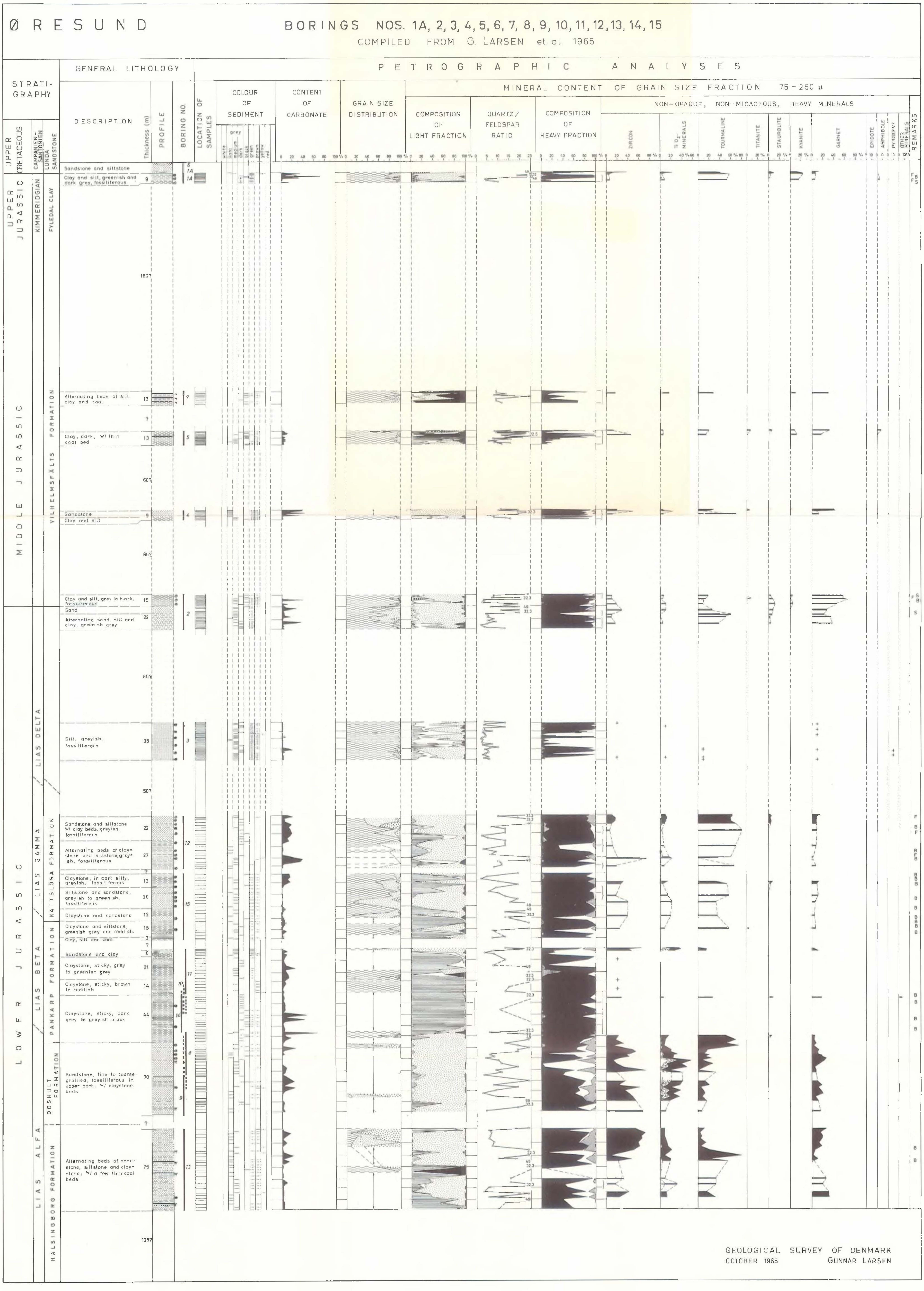

H O R S E N S NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965 GUNNAR LARSEN
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m under terræn
m below ground
m under platform
m below rotary-table
MODSTAND — RESISTIVITY
Ohm m²/m
Lateral AO=188"
Short normal AM=16"
Long normal AM=64"
UPPER CRETAC.
SENONIAN-TURONIAN
CENOMANIAN
LOWER CRETACEOUS APTIAN-ALBIAN
MIDDLE JURASSIC
LOWER JURASSIC
U. TRIASSIC
RHAETIC
KEUPER
Limestone and marl
1146-1165 m: KALKSTEN, grønlighvid glaukonitisk med bleg-grøn MERGEL og mørkegrå LERSKIFER
Marl and shale, reddish brown
1165-1170 m: MERGEL og LERSKIFER, rødligbrun
Shale, dark grey to brownish grey
1170-1220 m: LERSKIFER, mørkegrå til brunliggrå
Sandstone and siltstone pale greenish, glauconitic
1220-1294 m: SAND og FINSANDSTEN, bleggrøn, glaukonitisk
Shale, dark grey and greyish black with dark-brown beds, at the base dark-grey sandstone and siltstone
1294-1569 m: LERSKIFER, mørkegrå, gråsort, med mørkebrune lag. Nedre dele med mørkegrå SAND- og FINSANDSTEN.
Sandstone and siltstone, alternating with greyish black shale; lignite seams. In lower part thin beds of pale-grey limestone
1569-1642 m: SANDSTEN og FINSANDSTEN, vekselliggende med LERSKIFER, gråsort, bånd af LIGNIT. LERSKIFER, lysegrå og mørkegrå med brunlige bånd. Basalt bånd af bleggrå KALKSTEN
Claystone, brownish with gypsum
1642-1726 m: LERSTEN og LERSKIFER, rustbrun og varierende, med GIPS.
RØDBY FORM.
BØRGLUM FORM.
?HALDAGER? FORMATION
FJERRITSLEV FORMATION
GASSUM FORM.
?VINDING? FORM.
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
grey
white light medium dark black green brown yellow red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75-250 μ
COMPOSITION OF LIGHT FRACTION
QUARTZ/FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO₂-MINERALS
TOURMALINE
STAUROLITE
KYANITE
CHLORITOID
GARNET



ULLERSLEV NO. 1
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965 GUNNAR LARSEN.
STRATIGRAPHY
GAMMASTRÅLING
GAMMA - RAY
20 80 140 Impuls/sec.
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m. under terræn
m. below ground
Feet under platform
Feet below Rotary-table
MODSTAND - RESISTIVITY
Ohm m²/m
Ohm m²/m
UPPER CRET.
LOWER CRET.
ALBIAN
APTIAN
HAUTERIVIAN - APTIAN
TRIASSIC
RHAETIC
U. RHAETIC & KEUPER
Shale and marl, reddish brown.
801–820 m: SKIFERLER, rødbrunt, fedt.
RØDBY FORM.
Sandstone and clay.
820–826 m: SANDSTEN og LER.
VEDSTED FORM.
Short normal AM = 10"
Long normal AM = 38"
Inverse AO = 16'
Shale and claystone, dark to light grey, alternating with light grey sandstone.
826–978 m: LERSKIFER og LERSTEN, mørk og lys grå, afvekslende med SANDSTEN, lys grå.
ULLERSLEV FORMATION
Claystone, brown and green, with vari-coloured inclusions, with anhydrite in the lower part.
978–1060 m: LERSTEN, afvekslende brun og grøn, med brogede indeslutninger. Nedadtil med ANHYDRIT.
800
801
820
826
900
978
1000
1060
2600
2700
2800
2900
3000
3100
3200
3300
3400
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
grey
white
light
medium
dark
black
green
brown
yellow
red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 μ
COMPOSITION OF LIGHT FRACTION
QUARTZ/FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO_2-MINERALS
TOURMALINE
STAUROLITE
KYANITE
GARNET
EPIDOTE
HORNBLENDE
REMARKS


RØDBY NO. 1
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN.
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt
LITHOLOGI
LITHOLOGY
m. under terræn
m. below ground
Feet under platform
Feet below Rotary-table
MODSTAND - RESISTIVITY
Ohm m²/m
Short normal AM1 = 10"
Long normal AM2 = 38"
Inverse AO = 16'
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
white
light
medium
dark
black
grey
green
brown
yellow
red
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 – 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ/FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO2-MINERALS
TOURMALINE
TITANITE
STAUROLITE
KYANITE
CHLORITOID
GARNET
EPIDOTE
HORNBLENDE
PYROXENE
REMARKS
UPPER CRETACEOUS
CENOMANIAN TURONIAN
LOW CRET.
ALBIAN
LOWER JURASSIC
LIAS GAMMA
LIAS ALPHA
TRIASSIC
RHAETIC
U. TRIASSIC
KEUPER
Limestone and marl.
439–459 m: KALK, hvid, blød, meget MERGEL grønlig blåt
Marlstone, reddish brown w/ green spots.
459–469 m: MERGEL rødbrun med grønne partier.
Silt multicoloured.
469–470 m: FINSAND, broget.
Clay, dark grey to greyish black; interbedded with fine-grained sand, light grey; bone-bed at 531
470–531 m: LER, mørkt gråt til gråsort, afvekslende med SAND, fint, lyst gråt
531–532 m: FINSAND, "bone bed"
532–545 m: LER-SKIFER, mørk grønliggrå
545–547 m: LERSTEN og FINSANDSTEN, grå
547–557 m: LERSTEN finsandet, mørk grå.
Sand, fine grained, argillaceous, light grey; alternating with clay, silty, greenish grey.
557–686 m: SAND fint, leret, lys gråt afvekslende med LER, finsandet, grønlig gråt.
Claystone alternating with sand and sandstone light grey; in lower part shale and silt.
686–713 m: LERSTEN med SAND og SANDSTEN, lys grå kalkholdig; nedefter med LERSKIFER og FINSAND.
Claystone, greenish grey and brownish; w/anhydrite.
713–784 m: LERSTEN, lys grønliggrå til lys grøn, med brunlige partier og ANHYDRIT.
RØDBY FORM.
FJERRITSLEV FORMATION
ULLERSLEV FORMATION


L A V Ø NO. 1.
GEOLOGICAL SURVEY OF DENMARK
NOVEMBER 1965
GUNNAR LARSEN
STRATIGRAPHY
SELVPOTENTIALE
SPONTANEOUS-POTENTIAL
Millivolt.
LITHOLOGI
LITHOLOGY
m under terrain
m. below ground
m under platform.
m. below rotary-table
MODSTAND - RESISTIVITY
Ohm m²/m
Short normal AM = 16
Long normal AM = 64
Lateral AO = 18
UPPER CRETACEOUS
TURONIAN
ALBIAN CENOMANIAN
LOWER CRETACEOUS
LOWER JURASSIS
U. TRIASSIC
RHAETIC?
KEUPER
Limestone and shale
1866-1940m: KALKSTEN, hvid, nederst med LERSKIFER, mørk grønliggrå, glaukonitisk.
Siltstone, grey and shale, dark greenish grey; at the base green, glauconitic sandstone
1940-1996m: FINSANDSTEN, grå, og LERSKIFER, mørk grønliggrå; nederst: SANDSTEN, grøn, glaukonitisk.
Sandstone, whitish grey; shale dark grey to brownish grey
1996-2069m: SANDSTEN, hvidliggrå; LERSKIFER, mørkegrå, brunliggrå.
Shale, dark greenish grey; sandstone, fine-grained, light grey
2069-2290m: LERSKIFER, mørk grønliggrå; FINSANDSTEN, lysegrå.
Shale, greenish grey, brownish grey, greyish black; sandstone and siltstone
2290-2365m: LERSKIFER, grønliggrå, brunliggrå, gråsort; SANDSTEN og FINSANDSTEN.
Claystone, multicoloured reddish brown, green, yellow; sandstone, pale green
2365-2438m: LERSTEN, broget, rødbrun, grøn, gul, SANDSTEN, bleggrøn.
1900
1940
1995
2000
2069
2100
2200
2290
2300
2365
2400
2438
LAVØ FORMATION
? FJERRITSLEV FORMATION ?
LOCATION OF SAMPLES
COLOUR OF SEDIMENT
white light medium dark black green brown yellow red
grey
CONTENT OF CARBONATE
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 - 250 µ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO2-MINERALS
TOURMALINE
TITANITE
STAUROLITE
CHLORITOID
GARNET
REMARKS
0 20 40 60 80 100%
0 5 10 15 20 25
B
S



Ø R E S U N D
BORINGS NOS. 1A, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
COMPILED FROM G. LARSEN et. al. 1965
STRATIGRAPHY
GENERAL LITHOLOGY
DESCRIPTION
Thickness (m)
PROFILE
BORING NO.
LOCATION OF SAMPLES
PETROGRAPHIC ANALYSES
COLOUR OF SEDIMENT
CONTENT OF CARBONATE
GRAIN SIZE DISTRIBUTION
MINERAL CONTENT OF GRAIN SIZE FRACTION 75 - 250 μ
COMPOSITION OF LIGHT FRACTION
QUARTZ / FELDSPAR RATIO
COMPOSITION OF HEAVY FRACTION
NON-OPAQUE, NON-MICACEOUS, HEAVY MINERALS
ZIRCON
TiO2-MINERALS
TOURMALINE
TITANITE
STAUROLITE
KYANITE
GARNET
EPIDOTE
AMPHIBOLE
PYROXENE
OTHER MINERALS
REMARKS
UPPER CRETACEOUS
CAMPANIEN-SANTONIEN
LUNDA SANDSTONE
Sandstone and siltstone
UPPER JURASSIC
KIMMERIDGIAN
FYLEDAL CLAY
Clay and silt, greenish and dark grey, fossiliferous
9
180?
MIDDLE JURASSIC
VILHELMSFÄLTS FORMATION
Alternating beds of silt, clay and coal
13
?
Clay, dark, W/ thin coal bed
13
60?
Sandstone
Clay and silt
9
65?
Clay and silt, grey to black, fossiliferous
10
Sand
Alternating sand, silt and clay, greenish grey
22
85?
LOWER JURASSIC
LIAS DELTA
Silt, greyish, fossiliferous
35
50?
LIAS GAMMA
KATTSLÖSA FORMATION
Sandstone and siltstone W/ clay beds, greyish, fossiliferous
22
Alternating beds of claystone and siltstone, greyish, fossiliferous
27
?
Claystone, in part silty, greyish, fossiliferous
12
Siltstone and sandstone, greyish to greenish, fossiliferous
20
Claystone and sandstone
12
LIAS BETA
PANKARP FORMATION
Claystone and siltstone, greenish grey and reddish
15
Clay, silt and coal
3
?
Sandstone and clay
6
Claystone, sticky, grey to greenish grey
21
Claystone, sticky, brown to reddish
14
Claystone, sticky, dark grey to greyish black
44
DOSHULT FORMATION
Sandstone, fine-to coarse-grained, fossiliferous in upper part, W/ claystone beds
70
?
LIAS ALFA
HÄLSINGBORG FORMATION
Alternating beds of sandstone, siltstone and claystone, W/ a few thin coal beds
75
125?
GEOLOGICAL SURVEY OF DENMARK
OCTOBER 1965
GUNNAR LARSEN