3. Studies in the lithogenesis of the Cambrian and basal Ordovician of the Böda Hamn sequence of strata

By

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Contents

I. Introduction and acknowledgements

Changes of level of the land are a central problem in historical geology. Quaternary changes of level are the best known, not only because this period offers the best possibilities for the study of diastrophic processes but also because Quaternary changes of level have been very actively investigated.

The Quaternary changes of level are intricate and complex. There is no reason to presume that the changes of level in the Pre-Quaternary were less complex, nor that their mechanism was different. Studies of Pre-Quaternary changes of level are complicated by the fact that often only remnants of the formations are left and that the rocks have been more altered diagenetically.

Though the principal changes of level and the main distribution of land and sea during the Pre-Quaternary may be said to be largely known, the detailed development is obscure to a great extent even in classical areas of investigation. It is evident that studies of these questions must be based on careful examination of each separate locality in order to establish the continuous local relation between the level of deposition and the level of the sea. The possibility to elucidate regional changes of level depends on how far such local problems can be solved.

Studies of fossils alone are obviously not sufficient for this purpose: it is necessary to examine the sediment with the same care as the fossils, and the observations and analyses have to be checked by experience in recent sedimentology.

Equal shares of interest have been devoted to sediment and fossils in this investigation. The fossils were studied by Mr. B. WÆRN, Fil. Lic., and the sediment by the present author. Micro-fossils released in the disintegration of the rock for sedimentological purpose were accordingly turned over to Mr. WÆRN for examination. Mr. WÆRN and the present author had access to one another's results and use part of them in our respective papers. Mr. B. COLLINI, Fil. Lic., examined clay substances mineralogically. Mr. WÆRN's paper was published in 1952 in the Bulletin of the Geological Institution of Upsala. Mr. COLLINI's examination has not yet appeared in print.

The central problem in my part of the investigation was an attempt to reconstruct the environment of sedimentation during the time sequence represented by the core portion examined. This also involves the question of the local changes of level. A greatest possible number of indications were examined in order to base the conclusions on these ancient environments as safely as possible. This is necessary because certain similar sedimentary indications can appear in different types of environment and because the indicative significance of many sedimentary phenomena is still insufficiently known.

Indicators of uncertain environmental significance are recorded with the hope that they be better known when tied in this way with better established criteria.

I wish to acknowledge that I have had the privilege of discussing several problems of importance for the present investigation with specialists in Europe and America.

Thanks are extended particularly to Dr. L. M. J. U. VAN STRAATEN, of Groningen, for his guidance during my actuogeological studies in the Netherlands.

I am pleased to express my obligation to those who have assisted me in the laboratory: Mr. J. LUKINS, Dipl. Ing., and Mrs. E. LUKINA (chemical analyses), Miss M. WALLIN (granulometrical analyses and other assistance), Mr. G. ANDERSSON (preparation of thin sections), Mr. A. NILSSON (preparation of drawings), and Mr. N. HJORTH (photographs). I am especially indebted to Mrs. M. HESSLAND. Fil. Mag., for assistance in several respects. Dr. H. NÖMMIK kindly analysed a number of samples for fluorine.

The manuscript was finished in 1951.

II. Environmental indications

Indications of environment connected with the present locality are discussed briefly in this chapter previous to the description of the core and the interpretation of the ancient environments and the changes of level. This is made in order to avoid insertions of such discussions at different places in the text. Some indications of environment have been discussed by the author in earlier papers to which reference is made.

The sedimentary indications can be classified in three main groups. One comprises the composition of the sediment with regard to grain size, sorting, and other data based on size distribution, shape and roundness of particles, petrology, and chemistry. Bedding and other internal structures as well as "worm" tubes and borings of various kind can be referred to the second group. The third group includes surface structures, both inorganic and those formed by organisms.

A. Composition of the sediment

Grain size. Estimations of the depth of water on the basis of grain size alone are impaired with considerable uncertainty. As commonly known, the conception that the size of particles diminishes seawards with increasing depth cannot be maintained without restriction: besides being deposited in deeper water, fine sediments accumulate in shallow near-shore areas, often just below the water surface and then many times at higher levels than nearby coarser sediments. Change from comparatively coarse to more fine-grained sedimentation can occur not only when depth increases but also when it is chiefly constant or diminishing. Changes in bottom and coast configuration are important factors controlling this sedimentary development. Such changes can readily appear in areas with great movable sand masses, where the sedimentation changes with the exposure. Movements of sand masses on a large scale occur, for instance, on the eastern North Sea coast, where the islands move continuously (cf. e.g. PRATJE 1941).

There are a great many other reasons to be careful in calculations of the water's depth on the basis of grain size. For example, the sedimentation of fine-particles is influenced by the physico-chemical composition of the water, mainly the salinity; mass transportation by slumping and turbidity currents is certainly also of great importance. On the other hand, resistance against detraction of unconsolidated sediments can be different owing, for instance, to difference in compaction and to the presence of binding substances, both organic and inorganic. The size of particles can have changed secondarily both by growth and dissolution, and quite new particles can have developed, such as authigenic feldspar.

Considering, however, such difficulties, grain size and data derived from the size distribution are of basic significance as indicators of environment when put in relation to other environmental indications.

Shape and roundness of particles. Much work has been done in recent years in order to evaluate the environmental significance of these characters.

Concerning shape of particles we are interested inter alia in macroscopical mica flakes which may be indicative of the littoral zone (cf. PETTIJOHN 1949, p. 96). Since, furthermore, mica flakes, being transported in suspension, are deposited in fine sand and silt rather than in the bed-load sediment of congranulometrical coarse sand we may conclude that if coarse sand includes mica of the same order of size, shape-sorting has been of subordinate importance and that such a sediment accumulated rapidly.

With regard to roundness of particles, the roundness of quartz grains was evaluated in the present case according to a chart in PETTIJOHN (1949, p. 52); that of feldspar and heavy minerals was examined qualitatively to some extent. Roundness and shape of shell fragments were also studied.

The most favourable sites for rounding of grains are dunes and beaches, and abrasive processes on beaches seem to be more effective than aeolian abrasion (RUSSELL 1939, p. 37–43).

Larger grains are more rapidly rounded than smaller ones in sediments of polymictic granulometrical composition, because smaller particles are more susceptible to fracture and breakage. The size of minerals with good cleavage is readily diminished by such processes.

There exists, in other words, a correlation between size and roundness (and sphericity), and "the disparity in roundness shown by the largest and smallest fragments will increase as abrasion proceeds (up to a certain point). A mature sand or gravel, therefore, should show a well-marked correlation between size and roundness, whereas in an immature sediment such relationship is less pronounced" (PETTIJOHN 1949, p. 404). This means that roundness may be comparatively uniform in all sizes of rapidly accumulated weathering products. As abrasive processes work slowly, at least with regard to sand and smaller size grades, and exceedingly slowly in absence of coarse materials, a sediment of mixed granulometrical composition with the aforementioned disparity in roundness has undergone a long development of repeated reworking, wear, and transportation (cf., for instance, several quotations in PETTIJOHN's above-mentioned handbook, e.g. p. 53, 236, 403, and 411).

These basic facts now touched upon are important not only in reconstructions of ancient environments but also in interpretations of the rate of changes of level. Sediments distinguished by mainly the same degree of roundness in all size grades may have accumulated during rapid changes of level, whereas sediments characterized by distinct differentiation in roundness relative to size may indicate slow level changes. As a matter of fact, the quantities of supplied material and the previous roundness of the grains must be considered.

The process of rounding with general diminution of size by wearing and splitting is combined with selective processes which sort and classify. Larger rounded particles, transported by traction along the bottom, can be deposited at other sites than the smaller angular particles carried in suspension which are laid down in more quiet environment, often together with clayey substances. Yet, it happens that rounded quartz grains of about one millimeter or more in diameter are included in clay and shale layers. To my knowledge, the environmental circumstances in which such contamination takes place has not been examined. The "accessory" large grains were certainly not carried there by the wind, but by traction. The embedding into the clay may have occurred in the vicinity of the ancient shore, and "accessory" grains as now mentioned may appear to be useful as an indicator of near-shore deposition.

Flat-rounded shell fragments are common in part of the core, often in beds of angular silt or fine sand intercalated in clayey sediments. Abrasion of shell fragments takes place on the shore and by the oscillatory pushing movements to and fro in shallow water on open coasts. In recent environment it can be observed that flat-rounded shell fragments, fine-sand, and silt have been concentrated secondarily, forming thin layers in shallow clayey facies. Flat-rounded shell fragments certainly give no definite measure of the depth of deposition but merely indicate that the water was shallow.

Petrology. The rock sequence includes both detrital and newly formed minerals in part elucidative of the environment of deposition.

Detrital minerals. Quartz, mica, feldspar, and heavy minerals were examined mainly with regard to frequency, shape, roundness, and, as regards feldspar, the state of weathering.

Owing to the good cleavage of the crystals, feldspar can more easily split up in the process of wear and fracture than quartz; the hardness is, moreover, somewhat inferior. Yet, intense and long abrasion is necessary to eliminate unweathered feldspar and to produce a practically monomineralic quartz sand (cf. e.g. PETTIJOHN 1949, p. 94). Feldspar is, however, readily attacked by chemical action, and absence or weak representation of feldspar in transgressive sandstones can thus be due to destruction during the transgression because the parent rock had been strongly weathered. Poorness in feldspar alone — be it due to original low frequency in the parent rock or rapid destruction of weathered material — is apparently not a reliable indicator of the rates of accumulation and changes of level. On the other hand, abundance of weathered feldspar in the sediment can indicate great rapidity in accumulation and subsidence.

Heavy minerals have not been used here in order to ascertain the detailed provenance of the sediment, which is a task too comprehensive and special to be carried out within the scope of this investigation. The qualitative observations that were made can only give some intimation of the source of the sediment and, in connection with other indices, can be useful in the reconstruction of the ancient environments of deposition.

As, under current conditions, heavy minerals are not laid down in the same size grades as lighter minerals but, "lagging behind", among larger grades, they are not distinctive of well-sorted fine-sediments deposited after transportation in suspension (cf. CALDWELL 1940). They are often accumulated in shore layers. Comparatively large and well-rounded heavy minerals are sometimes intermingled in fine-sediments, like the aforementioned quartz grains, cf. p. 39. They may be in further support to these of dual mode of transportation indicating vicinity to the ancient shore.

Newly formed minerals. Pyrite, glauconite, phosphorite, hydrous iron oxide, and calcareous substances have been considered.

The author has discussed the significance of these constituents as environmental indicators in earlier papers and may refer to references and opinions advanced there. In the present connection, therefore, mainly complementary data on their indicative importance are added. The constituents are in part still impaired with uncertainty, and further study of their indicative significance is necessary.

Pyrite. The indicative significance of sulphur has been touched upon earlier by the author (cf. 1950, p. 52). Some additional facts with special reference to pyrite are mentioned below.

The formation of this diagenetic product seems to begin in an early stage of the diagenesis. In recent tidal flat sediments a layer of a few decimetres thickness somewhat below the surface is often coloured with black iron-monosulphide, whereas pyrite has developed in the underlying greyish sediment (cf. VAN STRAATEN 1950, p. 104). As the sulphur may originate from dead organisms to a considerable extent, the frequency of organic matter is of very great importance for the content of pyrite in the sediment. When the endofauna is abundant the sediment can be rich in pyrite, even if the water above the sediment is thoroughly ventilated. All oxygen penetrating into the sediment is consumed in the decomposition of the dead bodies, and a favourable environment for preservation of sulphur is created in the interstitial water; an example of this are the above-mentioned flats. Thus the frequency of pyrite (illustrated by the sulphur curve in the present case) cannot be used as an indicator of the depositional reduction-oxidation conditions in the free water without consideration of other collateral indices.

Glauconite. The chief factors supposed to rule the genesis of glauconite are: depth, temperature, acidity, movements and reduction-oxidation conditions of the water; furthermore, it has been discussed whether presence of organic matter and mud sediments is of importance.

The problem of glauconite formation is still not unraveled, but it seems evident that this mineral can be formed in different ways. In many cases it may be a precipitate but in others it may be formed by transformation of other minerals, such as biotite, but illite may be considered as well.

In case of such transformation within the sediment the physico-chemical conditions in the sediment are obviously of greater importance than those in the free water.

The above-mentioned factors are briefly evaluated below.

Depth is apparently not a critical factor in the formation of glauconite which is reported as being generated at depths ranging from a few feet (TAKAHASHI and YAGI 1929) to thousands of metres (cf. e.g. HADDING 1932).

Temperature of the water also does not seem to be of special importance. The suggestion by HADDING and other writers that glauconitization should be favoured in relatively cold water (HADDING 1932, p. 149 f.) is contradicted by TAKAHASHI's observations in Japan. According to this author (1939, p. 503 f.) the process is intensified along the western Japanese coast where the warm Kuroshiwo current coming from the Kurile Islands passes by. On the other hand, it can be learned from GALLIHER (1935) that glauconitization seems to occur within a rather considerable range of temperature.

The rôle of acidity of the water was discussed by HADDING (1932, p. 150) in linking up this question with that of temperature and tension of carbon dioxide. Because the genesis of glauconite is too little known, this mineral cannot yet, however, be used as a safe criterion on the acidity of ancient water bodies.

The movements in the water and the reduction-oxidation conditions are closely connected with each other as well as with organic matter and mud so far as the frequency of these constituents indicates the amount of movement of the water. Reduction-oxidation conditions obviously constitute the central question of this complex from a paleohydrological point of view. Here opinion stands against opinion and the writer is not inclined to agree entirely with any of them. With regard to glauconitic precipitates I have suggested that repeated alternation between periods of stagnation and ventilation might be favourable for their formation (cf. HESSLAND 1950, p. 54). This idea is supported by observations in the present core where, in shales, glauconite is confined to thin silty layers, certainly indicating temporary short ventilations. Many of these glauconite grains are several times bigger than the silty particles and cannot likely have accumulated secondarily at the same time as these. Yet, further investigations are necessary before glauconite can be used as an indicator of environments distinguished by such hydrological changes as now mentioned. Abundant formation of glauconite may, under special conditions, be indicative of transgressive movements (cf. HESSLAND, l. c.).

Phosphorite. The partly far-reaching correspondence in lithological occurrence of phosphorite and glauconite suggests that the supply of phosphorus to the sediment is governed largely by conditions similar to those controlling the formation of glauconite. This is supported by limnological investigations according to which inorganic precipitation of phosphate takes place at the change from stagnation to ventilation (cf. references and discussion in HESSLAND 1950, p. 53). Certain stagnant coastal water bodies can be supposed to be excellent traps for trivalent phosphorus which is precipitated instantly upon ventilation, but these environments have been too little studied hydrochemically and they have not been thought of as sites for formation of precipitated phosphorites. The environmental significance of phosphorite is still quite limited. The fact must also be considered that phosphorus is incorporated with the sediment with excretion products and dead organisms, and, moreover, that phosphoritic nodules can be readily redeposited.

Hydrous iron oxide. Precipitation of hydrous iron oxide can occur in ventilated coastal waters furnished with iron from the land but also in water bodies where, after enrichment during stagnation, iron is precipitated in the beginning of subsequent ventilation. Transportation to greater distance from the shore is not likely since hydrous iron oxide is hydrophobic and its solubility product is very low at the pH prevailing in the sea. Hydrous iron oxide is accordingly useful as environmental indicator to a certain extent, but may not be used for correlations over long distances. (Cf. discussion in HESSLAND 1949, p. 477.)

Calcium carbonate. In several cases it can be difficult to ascertain how calcareous layers were formed and their environmental significance, therefore, is limited.

Various factors governing the precipitation of calcium carbonate have been discussed earlier *i.a.* by the author (1950, p. 93). Certain thin calcareous layers of the present stratal sequence are possibly precipitates. Other calcareous strata are probably generated directly from calcium-bearing minerals, such as the anorthite section of the plagioclase group, hornblende, apatite, and titanite which all occur in weathered state in the underlying Archaean. The calcareous substance is probably also in part derived from trilobite carapaces to judge from the fact that those included in thin calcareous layers are strikingly thin.

In the present case the calcareous layers alone are apparently not suited to throw light on the ancient milieus of deposition, but they sometimes support other environmental indications.

Chemical elements. A few chemical elements of environmental significance were touched upon in the preceding discussion, viz., sulphur (in pyrite), phosphorus (in phosphorite), and iron. The total content of iron was established in the present case and is thus referable both to detrital minerals, not least certain clay minerals, and newly formed, above all glauconite, hydrous iron oxide, and pyrite (the pyrite iron has been subtracted and is represented by a separate thin line in the folding plate). Analyses of the special iron components would have been more valuable but could not be performed in this investigation. The iron curve as established here is, however, of environmental significance when checked by observations of iron-bearing minerals. It largely reflects the reduction-oxidation conditions, so far as it is running high in portions apparently laid down during periods characterized of relative stagnancy and running low in portions deposited in ventilated water.

Carbonaceous substances are closely associated with sulphur in indicative respect. In most cases they indicate low reduction-oxidation conditions but they can also be expected in certain sediments laid down in ventilated water similar to the aforementioned case of sulphur (p. 40), and the curve of carbonaceous matter must, therefore, be used with discrimination in discussions of ancient environments.

Chlorine. Salt-bearing enclosures of clay occurring in part of the lower Cambrian sandstone seem to have been eroded from sun-cracked clay layers deposited in shoals in the ancient shore area. These lumps cannot have been transported very far because the corners are generally angular. They apparently constitute good indicators of the level of deposition.

Fluorine. The fluorine content in a few selected samples throughout the core was analysed in order to examine whether there is any connection between the occurrences of fluorine and tourmaline. No such connection was ascertained. The fluorine is likely to a great extent confined to apatite.

Potassium was investigated in some lithologically characteristic samples in order to examine whether there is parallelism to radioactivity. A certain amount of such parallelism certainly exists.

Radioactivity. The gamma radiation was determined. This factor is complementary of grain size distribution and petrological and chemical composition.

According to RUSSELL (1944), radioactivity is very low in pure limestones, dolomites, and sandstones, but higher with increased quantities of clay substances and organic matter. The radioactivity of shales is considerable, and the darker the shale, the higher is the radioactivity. The highest frequency appears in oil shales and volcanic ash (including bentonite). The radioactivity of arkoses is said to be intermediate between those of pure sandstone and shales.

The radioactivity of glauconite does not seem to have been studied, and the writer, therefore, examined a few glauconitic sediments and found that the radioactivity is comparatively high; in a basal Ordovician glauconitic clay from Kårgärde, in Dalarna, for instance, it is about equal to that of the black shale of the present core.

Radioactivity as a criterion on ancient environments must be used with discrimination, since it can be caused by constituents which generally appear in quite different types of environment, such as certain heavy minerals indicating agitated water and, on the other hand, organic and inorganic fine-sediments occurring in quiet water. Observations of the mineralogical composition of the sediment is informative in this respect.

Different opinions on how radioactive substances are incorporated with the sediment have been advanced. The course of the curve of radioactivity in the present case shows great similarity to that of sulphur. For instance, the average frequency of radioactivity in the division 84—41 m which is chiefly argillaceous shale is 2.2 times smaller than in the division 40.5—39.5 m which is black shale; corresponding figure for sulphur is 2.1. However, the radioactivity can be comparatively high also in sections where sulphur is absent or its frequency is very low, such as section II. Concerning the relation between radioactivity and carbonaceous substances, the average frequency of the former is 2.2 times greater in the black shale than in the argillaceous shale as mentioned above, whereas that of the carbonaceous substances is 46.8 times greater; on the other hand, the radioactivity can be considerable in sections where carbonaceous substances are absent.

The curve of total iron exhibits the most far-reaching correspondence with the curve of radioactivity. The iron curve reflects chiefly the frequency of clayey matter, and the similarity in the general courses of the curves indicates that conditions for incorporation of radioactive components were favourable during such periods when clay substances were deposited, i.e. during largely quiet periods. Part of the radioactivity is certainly caused by the active isotope of potassium (K^{40}) which occurs in the shales. To judge from our analyses, there is essential correlation between the frequencies of potassium and radioactivity, as long as the amount of carbonaceous matter is low. The radioactivity is increased in sediments with high contents of carbonaceous matter but not nearly in proportion to the latter (cf. above). The radioactive isotope of potassium is also responsible for part of the radioactivity of glauconite.

As a matter of fact, the environmental circumstances for incorporation of radioactivity with sediments of the present type are not entirely known, but so much may be said, viz. that, as a rule, comparatively high radioactivity indicates deposition during mainly stagnant conditions, whereas a low frequency or absence suggests deposition in agitated water.

B. Internal structures

Rather comprehensive information on internal structures can be obtained from longitudinal sections in drill cores in spite of the fact that these surfaces are small.

Many primary structures are correlated with the grain size, and coordinated studies of structures and grain size can be of great use for the understanding of certain features of ancient sedimentological processes, especially water movements. However, detailed estimations of the depth of water can be made only in a restricted number of cases.

Mud-flats above highest mean tide are often characterized by thin and straight lamination. Owing to the long intervals between the inundations of such mud-flats, sun-cracks can be expected there, which give further support in indicatory respect on the level of deposition. Crack-fillings of coarser, less compactable sediments are often ptygmatized (cf. Plate I, Fig. 2; also cf. BRADLEY 1930). Pushing movements probably caused by tangential action of wind upon the re-soaked sediment or by water movements during floodings have often resulted in additional irregular shapes of the ptygmatized fillings.

The conform, slightly dipping bedding of sand sediments, so characteristic of beaches, also indicates the level of deposition. A certain amount of care may be taken, as the off-shore internal structures are still unsatisfactorily known.

Current bedding and internal structures of ripples as well as scour and fill structures give valuable information on the water movements but they are generally not reliable as criteria on the depth of the water. If identifiable, which, however, can be a difficult task, the foreset bedding formed in tidal flat areas by the constantly moving gullies (German *Priele*) can be of considerable help in reconstructions of ancient environments.

Flow and plunge structures formed when coarser materials are swept in with currents or waves over semifluid fine-sediments indicate water movements but nothing definite on the depth.

The thickness of beds of minerogene fine-sediments may give some intimation of the salinity of the water. Fine laminations can be expected in fresh water or in water with low salinity, such as certain enclosed coastal water bodies, where the sedimentation is less influenced by electrolytic agglutination than in the open sea (cf. SAURAMO 1923, p. 91 f.). Laminated structures also appear in certain areas with high salinity, especially under the influence of the tide. In exposed sandy tidal flats the fine-grained laminae are of very restricted extension and more or less irregular (cf. for instance HÄNTZSCHEL 1936). Tidal lamination of greater extension appears in more sheltered areas, e.g. the shallow parts of flats in funnel-shaped mouths of large rivers and deeply incised bays (cf. HÄNTZSCHEL 1939), as well as in basins with narrow opening (such as the Arcachon Bay on the French Atlantic coast).

Vertical "worm" tubes are not sufficiently known to serve as cogent environmental criteria. Tubes formed by ascending entrapped air are reliable in this respect, however, occurring in the upper part of tidal beaches. The author has observed such air channels in some American beaches, for instance at the Chesapeake Bay (cf. also HÖGBOM 1915). They are less regular than those formed by tube-building beach endobionts. On the eastern North Sea coast polychaet tubes are characteristic of the low parts of the beaches. Crustacean tubes, often U-shaped, are common in tidal flats in this region. Vertical tubes are undoubtedly suited for tidal beaches with their special ecological conditions, as the tube inhabiting polychaets readily can withdraw to the lower water-soaked part during low tide. Whether vertical tubes of the same appearance as those occurring in tidal areas also appear in constantly covered sea bottoms does not seem to be known according to information from experienced European and American marine zoologists. For this reason, vertical tubes formed by animals cannot be considered as perfectly reliable indicators of the level of deposition.

Vertical tubes in fossil sediments have often been used as evidence for deposition in the tidal zone. RICHTER (1920) compared pipe-rock tubes with those of the recent polychaet *Sabellaria alveolata* L. which forms so-called sand riffs in the tidal area of the German North Sea coast by its closely set tubes. The walls of these tubes are comparatively firm and may not correspond to the pipe-rock specimen *Scolithus* which is represented in our core. The walls of *Scolithus* were apparently less rigid. They were probably also less rigid than those of another common tube-builder on the eastern North Sea beaches, viz. *Lanice conchilega* DALL. The *Lanice* tubes are often released from the bottom by erosion and deposited on the shore, sometimes in small heaps. This was not true for *Scolithus*, as far as I know. The tubes of *Nerine cirratulus* (DELLE CHIAJE), another member of the tube-builders of the North Sea beaches, are very soft and the walls are so thin that they are discernible only exceptionally, and I think that these tubes can be compared to the *Scolithus* tubes.

Nerine cirratulus is very common on the beach but it also lives offshore. According to records kept at the Zoological Station of Den Helder, in Holland, it has been found down to nearly 20 m depth. Dr. SCHÄFER, of the Senckenberg Institute, in Germany, informed me that the frequency in these permanently submarine sites is by far less than that of the beach. It does not seem to be known whether *Nerine* forms vertical tubes in its submarine habitats. I have observed that the animals build irregular tubes when transferred together with the sediment into glass jars and the sediment is covered with water.

More or less winding and irregular burrows, part of them being largely horizontal, do not indicate anything definite of the water's depth.

C. External structures

Structures and marks developed on more or less regularly uncovered bottoms are among the most positive indications of the level of sedimentation. Rain drop imprints, mud-cracks, foam and swash marks, and crescent-shaped excavations around small objects on the shore constitute unmistakable such features. Mainly parallel and often anastomosing tiny ridges are the most common swash marks in our core (Plate II, Figs. 1—2).

Several other criteria on shore environment could be mentioned, such as superficial cavernulae raised into domes, craters formed by collapsed such domes, and rill marks of various types, but they have not been noticed in the present core.

Tracks of various animals and dragging trails are common on temporarily uncovered bottoms, especially those consisting of muddy sediments, but they also occur on constantly covered bottoms, so they cannot be used as criteria on the level of deposition.

Ripples are mostly also unfit for this purpose. Besides in shallow areas they can develope at various depths. Oscillation ripples with wave length up to a few centimetres most certainly indicate very shallow water but larger ripples of oscillation type have been discovered recently by underwater photographing at depths amounting to hundreds of metres.

III. Laboratory methods

A. Granulometry

The size distribution of the particles was established by mechanical analyses after disintegration of the rock samples.

Chemical agencies were avoided in the disintegration, because so active chemicals would have been necessary that the particles, especially clay minerals, would have been partly dissolved. Instead, one or more of the following methods were used:

1. Mechanical crumbling
2. Disintegration with white spirit (a petroleum product)
3. Ultra-sonic treatment.

Certain sandstones free from clay substances could be perfectly disintegrated with the fingers, but the majority of the sandstone samples were crumbled by means of slight pressure in a copying press, and the larger particles released were successively removed in order to avoid their crushing. Sandstones consisting of mainly rounded grains and with kaolin and similar fine-grained materials as interstitial matter were also treated in this way. To accomplish the disintegration the samples were kept for 30 minutes in a modified PHILIP ultra-sonic apparatus with a capacity of 20 000 cycles (220 V, 3-phase A. C.).

Alternation between high and low temperatures was also tried, but this procedure had no obvious effect. The low temperatures were produced by fluid oxygen (thus towards $-200°$ C).

Most of the sandstone samples weighed 50—60 g., but those with coarser constituents up to about 120 g. The quantities used for disaggregation of shales, cf. below, were 20 g., or 40 g. in case coarser materials were included.

Long time treatment and/or boiling with acids and strong alkalies are widely in use for disintegration of shales and mudstones in order to release fossils. Such methods are useful in these cases, but they cannot be employed in disintegrations for granulometrical purpose because of the dissolving effect of the chemicals, as mentioned above. Boiling in water may be practicable for little indurated mudstones and shales.

Another non-chemical method is reported as being effective for indurated shales, viz. steam forced into the rock under high pressure; TAYLOR and GEORGESEN (1933) worked with 350 pounds per square inch. In the present case another method was employed which is very active and mild at the same time. It is also advantageous in being simple, no complicated apparatus being requisite. This method was invented a few years ago by micropaleontologists who make use of it for release of foraminifera. It was briefly described by LAYNE 1950. When now applied to granulometrical disintegration it is only slightly modified. Instead of petrol (Amer. gasoline), white spirit was used, as this appeared to be somewhat more effective. The samples were treated in the following way.

After expulsion of the interstitial moisture at 105° C, the samples were placed in white spirit to remain there for two hours. This fluid was thereafter decanted and replaced by water. After a short time the samples began to swell and split up along the bedding planes. As the process continued the samples fell into smaller and smaller pieces. The disintegration was facilitated by adding a few drops of hydrogen peroxide and by stirring at intervals with a glass rod. Argillaceous shales without or with a very small content of carbonaceous substances disintegrated in a few hours, but the process was prolonged with increasing content of carbonaceous matter; the highly carbonaceous black shale could not be broken down at all. The method was useful in the present argillaceous sandstone (the so-called crow rock).

In a few calcareous samples the insoluble particles were freed by treatment in cold dilute acetic acid.

After the disintegration, particles smaller than 60 μ were detached by washing through a sieve of this mesh under continuous brushing. The generally small quantities of non-disaggregated residues left on the screen were subjected to ultra-sonic treatment during 30 minutes for further disaggregation.

The released particles larger than 60 μ were screened for one hour. The screen series was: 2—1—0.5—0.25—0.125—0.06 mm.

The particles smaller than 60 μ were suspended in an N/1000 solution of sodium oxalate and rotated in bottles for 24 hours. Ammonia appeared to be useless since it caused flocculation in certain samples. Thereafter, pipette analyses were carried out down to such a size grade that the median diameter and the quartiles could be read from the cumulative curves (cf. below).

It was established by microscopical control that a minority of particles often formed minute aggregates which could not be disaggregated by means of our methods These aggregates have slightly influenced the size distribution, and for this reason the distribution of particles smaller than 20 μ have not been reproduced. Accordingly they have also influenced the median diameter and the sorting to some extent. The curves which represent these characters throughout the stratal sequence are nevertheless sufficient to show their continuous general changes.

The size distribution is represented in the folding plate, partly all grades in one column, and, for the sake of a better general view, also each size grade separately, thus: > 2 mm; 2—1 mm; 1 mm—500 μ; 500 μ—250 μ; 250 μ—125 μ; 125 μ—60 μ; 60 μ—20 μ; < 20 μ. The median diameter and sorting are also given. The median diameter, the first and third quartiles (Q_1 and Q_3, resp.) were read from the cumulative curves. The sorting coefficient was calculated from the formula $\sqrt{Q_3/Q_1}$ according to TRASK (cf. KRUMBEIN and PETTIJOHN 1938, p. 230).

With regard to sorting, coefficient values smaller than 2.5 are stated to indicate good sorting, values about 3.0 normal sorting (values 2.5—4.5 indicate "sorted" sediments), and values higher than 4.5 poor sorting (TRASK 1932, p. 72). Other authors have considered these figures too high. STETSON and UPSON (1937, p. 57) are of the opinion that 1.45 is an average value of well-sorted near-shore sediments.

B. Chemistry

The contents of iron, phosphorus, sulphur, and carbonaceous substances were established by methods identical with those used by the author in similar earlier investigations (HESSLAND 1949, p. 57 and 1950, p. 448).

The following methods were employed in the other cases.

Calcareous substances. The frequency was examined by solution in dilute hydrochloric acid. (The carbonate consists practically only of $CaCO_3$.)

Oil content was determined by Dr. G. ASSARSSON of the Geol. Survey of Sweden by the method described by him in WESTERGÅRD 1940, p. 52.

Extraction of hydrocarbons by means of chloroform was made in a SOXHLET apparatus.

Vanadium. The sample was ignited at a temperature of 400—600° C and digested by means of sodium peroxide. After removal of the silica the main quantity of iron was detached by shaking with ether and the metal bases by precipitation with sodium hydroxide. Metals forming acids were left in the solution as sodium salts. Vanadium was separated with manganeous chloride as manganeous vanadate, which was dissolved and converted into a quadrivalent vanadyl salt. Its quantity was determined by titration with potassium permanganate.

For the removals a double separation funnel was used.

Potassium. The pulverized sample was digested in calcium carbonate and ammonium chloride. The alkali chloride was dissolved in water and filtered. The potassium of the filtrate was precipitated as potassium perchlorate.

Chlorine. The sample was boiled in water and the solution was filtered. Chlorine was precipitated with silver nitrate.

Whether the chlorine occurred as potassium or sodium chloride was examined qualitatively with flame colouring.

Total content of salts. The drilling water of certain levels in the boring was analysed with regard to its total content of salts by determination of its conductive capacity by means of a universal measuring bridge, "Philoscop", manufactured by Svenska Aktiebolaget PHILIPS, and a measuring cell, also produced by this company.

C. Radioactivity

was analysed with a GEIGER-MÜLLER counter. A gamma-sensible tube with tungsten cathod and copper anod was used (copper sublimated on the glass). The tube was manufactured by Svenska Elektronrör AB.

The measurements were made in a leaden box to diminish he influence of cosmic radiation.

D. Porosity

The apparatus described in HESSLAND 1950, p. 55 f. was used for the determination of porosity.

E. Separation of glauconite

A modified BERG method was employed (cf. HESSLAND-LUKINS-FREDÉN 1949).

F. "Development" of internal structures

Beddings and other internal structures are obscure or not discernible at all in many sandstones. They can often be "developed" by a simple procedure, viz. by heating in a flame.

Certain black and rounded grains, superficially reminiscent of magnetite grains appear in part of the Cambrian sandstone. They are generally too small to be seen macroscopically. They mainly consist of some asphalt-like substance and an iron compound, probably iron oxide. The specific gravity is about 2.2 (determination in CLERICI solution). They are pos-ibly faecal pellets (cf. e.g. WETZEL 1937). In the binocular they can often be observed arranged along bedding surfaces. When the rock specimen is heated in the flame the asphalt-like substances burn up and the minute cavernulae thus formed become surrounded by spheres of brownish substances of such dimensions that they can readily be seen by the naked eye, and thus indicate the bedding (Plate II, Fig. 3).

By this procedure other structures can also develop, such as clay laminations and *Scolithus* tubes.

Greenish clay substances which are indistinctly visible in the rock often stand out in photographs taken with high contrast panchromatic plates.

IV. Description of the core

The diameter of the core is 42 mm below 92.44 m and 71 mm above this level.

Losses of core in the drilling were rather small; only in a few portions are they conspicuous, viz.: 152.5—149.1 (0.3 m); 130.6—123.5 (0.8 m); 110.3—107.1 (0.3 m); 100.5—91.2 (2.8 m); 44.8—41.1 (1.1 m).

The description below of the division 162.15—about 39 m, comprising the Cambrian and basal Ordovician parts of the core, is based on data obtained in the following way.

The core was split lengthwise and across in its entire length and the pieces were inspected with the naked eye and at 15 times magnification. Particles freed in the disintegration of samples generally from each full metre were examined binocularly. Thin sections from each full metre and, partly, from half metre levels were studied in the microscope. Granulometry, comprising distribution, median diameter, and sorting (samples generally from each full metre level); gamma radiation, given as number of impulses per minute; and porosity, were measured (samples in both cases from half metre levels). Chemical analyses of the following constituents were carried out throughout the core: iron (given as oxide), sulphur (given as element), carbonaceous substances (given as C), phosphorus (given as phosphoric anhydride), and calcareous substances. These samples were taken from half metre levels except for carbonaceous substances which were partly analysed at full metre levels only. A few special analyses from selected levels were also made, viz.: oil and gaseous hydrocarbons, vanadium, potassium, chlorine, and fluorine.

The Archaean and the Ordovician portions of the core, except for the basal part of the latter, will be described by other authors; porosity, radioactivity, and chemical data will, however, be mentioned in the present connection. These measurements and analyses were carried out under my supervision.

The Cambrian part of the column is divided into nine sections according to the main lithological composition. They are numbered I to IX (I in the bottom, IX in the top).

The main lithology of the core is given in the head column of the folding plate and special components are represented in side columns.

The distribution of macro-fossils is referable to Mr. WÆRN's examination, but the occurrence of silicious micro-fossils (foraminifera, according to Mr. WÆRN) released in the disintegration of the rock for sedimentological investigation refers to my personal observations. This is also true of the *Scolithus* structures.

The Archaean

The porosity is low but increases upwards. The highest value noticed is 7 %.

Compared with section I of the Lower Cambrian the gamma radiation is rather high. The tendency is slightly rising upward from 9 to 12—13 impulses.

No indications of sulphur and carbonaceous substances were observed. The iron content is high (4.48—7.15 %). The phosphorus frequency is comparatively high in the lower part (0.41—0.66 %) but diminishes gradually in the upper. Calcareous substances were observed at one level, viz. 163.5 m (7.6 %). A separate analysis from the Archaean (163.5 m) showed 3.82 % potassium oxide. Another analysis of fluorine from 163.95 m indicated 1.53 parts per thousand, that is about 9—12 times more than in the Cambrian portion of the core and about 5 times more than in the Lower

Ordovician black shale. The high content of fluorine in the Archaean is probably due to apatite.

Further information on the Archaean will appear in a paper in preparation by Prof. H. G. BACKLUND.

Lower Cambrian

The Lower Cambrian part which rests directly on the Archaean measures 78.04 m and includes the division 162.15—84.11 m. The main component is sandstone, in part very pure quartz sandstone and in part interstratified with laminations of argillaceous substances or glauconite. The laminations have been greatly disturbed in some sections by the action of endobionts. *Kråksten* ("crow rock") is the common local name of the clay-laminated sandstone of the Kalmarsund district. The sandstone can also be filled up rather uniformly with clay substances which render the rock a greyish-green hue. The interstitial substance of the sandstone consists sometimes of kaolin-like material.

I. 162.15—150 m. This section is a very pure sandstone of white or somewhat greyish colour. The rock is occasionally so loose that it can be crumbled with the fingers. Clay laminations are few, occurring mainly in the upper part. Scattered small clay lumps are included with greatest frequency in the topmost metre of the section. Most of them taste slightly salty which is not the case with the stratified clay substances. The chlorine content of such an enclosure from the level 153.70 m was 1.01 %. At 150 m the salinity of the outgoing drilling water was 0.16 % higher than that of the ingoing Baltic water (0.65 and 0.49 %, resp.); no difference was noticed in the Archaean and the higher sections.

The porosity is moderate and fluctuates comparatively little. In the lower part the curve oscillates around 15 % and in the upper around 20 %.

Beddings are frequently discernible, often because of granulometrical stratification. The angles of bedding vary considerably and the changes are often very rapid. Maximum angles of bedding of 20—30° are fairly common in the lower half of the section, but the layering is often horizontal just above or below. It also happens that the bedding changes more or less gradually from about 10° in one direction to about 10° in the opposite within a vertical space of a few centimetres. In the upper half of the section great angles of bedding are less frequent and alternations in direction were not observed.

Practically no signs of displacement were noticed; only a few minute slickensides were observed in a somewhat clayey stratum at 152 m.

The median diameter of the lowermost sample (162.10 m) is the greatest observed in the core (0.88 mm). However, within one half metre it decreases to about 450 μ and remains then for the most part about 300 μ.

Particles remaining on the 5.6 mm screen were observed only in the lowermost sample (0.7 %). Particles of the size 5.6—4 mm were noticed up to 160 m (162.1: 0.6 %; 161.4: 0.1 %; 160: 0.3 %). The fraction 4—2 mm is represented up to 159.1 m (highest values in the two lowermost samples: 10.7 and 7.0 %, resp.) and in a single sample, viz. 156 m (0.1 %). The fraction 2—1 mm constitutes a continuous curve throughout the section, but appears only sporadically and in small quantities at higher levels. The highest frequency appears in the lowermost sample (32.8 %). The frequency is low in the remaining part; the average value above 161.4 m is 1.2 %. The next fraction in order (1 mm—500 μ) is well represented throughout the section, viz. with an average frequency of 21.6 % (max. 32.5 %, min. 6.1 %). The fraction 500—250 μ has the highest frequency, average 37.5 % (max. 56.7 %, min. 32.2 %, apart from the lowermost sample which has a frequency of 15.5 % only). The curve of the fraction 250—125 μ rises in the beginning and runs then highest next to that of the fraction 500—250 μ (average for the section: 25.0 %; max. 41.0 %, min. 10.7 %). Particles smaller than 125 μ play a subordinate rôle, especially in the lowermost part of the section; the average values for the section are: 125—60 μ = 6.3 %; 60—20 μ = 1.4 %; < 20 μ = 1.2 %.

Sorting is good for the most part; it is somewhat poorer in the bottom and top than in the intervening samples (coefficient about 1.9 and 1.6, resp.).

The larger quartz grains which are generally well rounded are mostly dirty buff-coloured or slightly brownish. Many of the small quartz particles have grown secondarily into crystals, especially in minute cavities.

Feldspar occurs throughout the section in accessory quantities. The frequency is somewhat higher in the bottom-most sample but arkose was not laid down during the initial phase of the sedimentation. The grains consist of generally weathered microcline in part rounded and in part angular.

Mica is represented by very small quantities. Single grains of chloritic and glauconite-like minerals occur in several samples; the latter were observed even in the bottom-most sample. A few crystals of a hitherto unidentified mineral which appears as needles (often twins) and is yellowish in colour and of metallic lustre was found in the samples below 159 m; they are most abundant in the bottom-most sample. Phosphoritic nodules were not noticed.

Well-rounded tourmaline grains are comparatively abundant, particularly in the upper half of the section. They are generally smaller than 125 μ. The colour is brownish, sometimes light brownish and in this case the grains are somewhat transparent. Black nodules interpreted as coprolites (cf. p. 51) appear constantly in small quantities below 158 m and occasionally above this level.

Thin layers of calcium carbonate are present in the bottom part of the section (at 162 m about 1 cm and at 159 m about 15 cm).

Kaolin-like substances occur as a fine dust throughout the section. They are mostly rather uniformly distributed in the rock but of somewhat higher frequency at some levels. In the coarse sediment resting just upon the Archaean they have sometimes been enriched as thin strata. Well-rounded quartz grains in other thin layers at different levels are often coated with kaolin dust. Narrow, mainly vertical tubes are sometimes filled with kaolin; they may also be filled with small-sized quartz grains.

In the lower half of the section the iron content is low and fluctuates very little; the curve has a slight tendency to increase upward (from about 0.5 % to 1.0 %). In the upper part, on the other hand, the fluctuations are rather considerable, thus initiating the development in the overlying section.

Carbonaceous substances are absent but scattered pyrite crystals were observed. No phosphorus was proved except in the uppermost 3 metres where small quantities occur (maximum 0.04 %). The fluorine content in a sample from 156.5 m was 0.127 parts per thousand.

In the lower part of the section the rock exhibits no radioactivity or only traces. In the upper part the majority of the samples are radioactive but the frequency is low (mostly less than 5 impulses, in a few cases somewhat higher, maximum 8 impulses).

No fossils were observed. Vertical tubes are similar to *Scolithus* tubes, and the pyrite grains are possibly of organic origin. The minute black nodules mainly consisting of some asphalt-like substance and some iron compound, probably iron oxide, are presumably coprolites.

II. 150—134.5 m. This section is chiefly developed as "crow rock" of greyish-green colour. It is abundantly traversed by essentially vertical winding burrows. Parts of the "crow rock" is dark brown-red from hydrous iron oxide, viz. some layers between the levels 144.5 and 138.6 m. In the layers 140.5—140.2 m and 139.2—139.0 m the hydrous iron oxide occurs as distinct laminations interstratified with fine-grained greenish substances. In thin sections it can be observed that the laminations of hydrous iron oxide appear for the most part in beds of larger grain size rather than in the greenish-grey matrix. Burrows are less frequent at the levels where the hydrous iron oxide is most abundant.

Some beds of a few decimetres thickness consist of whitish semiquartzitic sandstone, sometimes with a slight tinge of green.

The rock is chiefly well consolidated, especially the white sandstone beds. Parts of the "crow rock" with rather uniformly distributed clay substances are somewhat loose.

Greyish-green clay lumps occur at several levels, both in the "crow rock" and in the white sandstone beds; in the latter the lumps are in part imbricated. Some of the clay lumps have a slight taste of salt; these are most common around the 150 m level, and the uppermost appear at 142.3—142.1 m.

Analyses of the chlorine content in such clay lumps gave the following results: 143.95 m – 0.30 %; 142.15 m – 0.51 %; 140.55 m – 0.42%. The chlorine content in a reddish-brown layer in "crow rock" at 144.4 m was 0.19 %.

Bedding stands out by alternating stratification of greyish-green clay matter and kaolin-like substances, and occasionally it is indicated by dark heavy minerals and asphalt-like nodules. The angles of bedding can change from zero to about 10° within a vertical space of a few centimetres; such changes are often gradual. Cross-bedding under an angle of up to 25° was noticed.

Mud-cracks were observed at 144.8 m.

Slight dislocations can be seen in clayey parts. They may be due to the load of the overlying sediment and probably also to growth of quartz grains, especially in burrows. It can be observed that clay laminations have been pressed down by the lower end of burrows filled with such quartz grains. The clayey walls of these burrows have been squeezed.

Fluctuations in porosity are fairly considerable and rapid. Maximum values extend to 25—28 %, whereas the lowest ones amount to about 10 %.

The curve of the median diameter has a largely falling tendency up to 141 m (44 μ), but above this level it is chiefly rising. Most of the curve runs between the limits of about 75 μ and 175 μ. The absolute minimum is the aforementioned value of 44 μ and the absolute maximum is 400 μ (148 m). Some complementary analyses of samples from levels other than those analysed in the series exhibited somewhat higher values.

The largest size grade represented is that of 2—1 mm, but the occurrence of these particles is sporadic and the frequency is low (0.04—0.4 %). The curve of the fraction 1 mm—500 μ is mainly falling up to 141 m, but a single high value appears at 148 m (36.3 %). Above the 141 m level the average frequency is only 1.1 %. The fraction 500—250 μ continues from the previous section with comparatively high values up to 143 m (mean 26.4 %). Thereafter the frequency falls rapidly, but after 141 m begins a general tendency towards a gentle increase which continues in the overlying section. The fraction 250—125 μ dominates among the size grades (mean 29.7 %). The frequency of the fractions smaller than 125 μ has increased considerably compared with the underlying section (mean values: 125—60 μ = 22.3 %; 60—20 μ = 16.1 %; $<$ 20 μ = 9.9 %).

The sorting is not so good as in the previous section and the coefficient fluctuates more. It centres for the most part around 2 (max. 2.4, min. 1.5).

Many of the larger rounded quartz grains in the lower part of the section are dark. The smaller grains, especially, have often grown secondarily by extraneous crystallization. Crystals appear particularly in small cavities and in the burrows, where they are localized mainly to the central part. The quartz grains in the white sandstone beds are generally more coated by such newly formed crystals than those of the clayey layers.

Feldspar occurs in accessory quantities in most of the disintegrated samples. The particles generally consist of weathered microcline and are mostly angular. One large unweathered crystal of potassium feldspar was observed at 146.6 m.

Mica is practically absent in the white sandstone beds, but is common in the argillaceous layers, generally in the form of extremely thin flakes which seem to be authigenic.

Single grains of chlorite-like and glauconite-like substances appear in most of the samples. They occur invariably together, and in those samples where chlorite-like minerals are absent also the glauconite-like grains are missing. Small crystals of pyrite were observed in the lower and, in greater frequency, in the upper part of the section. Tourmaline grains, brownish and generally well rounded, were noticed in the size grade of 125—60 μ in practically all samples. Garnet crystals were found at some levels in clayey strata and in the clay filling of a vertical tube. Black, rounded nodules interpreted as faecal pellets (cf. p. 51) were observed in small quantities in the lower and middle parts of the section. Calcareous substances were not noticed, and phosphorus is entirely absent or the frequency is very low (maximum 0.03 %).

Kaolin-like dust is present in most parts of the section except the quartzitic white beds. It is generally rather uniformly distributed in the rock but is also concentrated in thin strata. Winding burrows are filled with this substance to some extent.

At the transition from the underlying section the iron curve forms a deep and practically symmetrical inflexion so that the frequency at the boundary is only 0.72 %. After the rise in the bottom of the section the curve oscillates moderately up to about the midheight (1.5—3.2 %), but in the upper part the amplitudes of the fluctuations are greater (0.8—5.0 %).

The fluorine content in a "crow rock" sample from 148.8 m is 0.168 parts per thousand.

This section shows radioactivity throughout but the frequency is mostly moderate, viz. about 5—10 impulses, at a few levels even less (minimum one impulse), but at others 12—14 impulses were measured. These higher values are predominant in the uppermost part of the section.

No fossils were observed but the presence of organisms is indicated by the winding burrows and probably by the pyrite crystals and the black nodules interpreted as faecal pellets.

III. 134.5—124 m. This section consists of white sandstone. Clay substances occur in subordinate quantities. Both greenish-grey clay substances and kaolin-like matter constitute locally fine laminations. A thin layer of greenish mudstone was also developed. Clay lumps are common throughout the section. The majority of them consist of a kaolin-like substance and a few are greyish-green clays; some of the enclosures have a slightly greenish tinge and seem to be intermediate between the greyish-green clay and the kaolin-like substance.

The consolidation is good for the greater part but at some levels the rock is so loose that it can easily be crumbled with the fingers and some losses of core during the drilling occurred on account of the weak consolidation, especially between 130 and 128 m.

In the lower and upper parts of the section the porosity varies fairly gently between 18.5 and 25.5 %, and in the intervening portion between 10.5 and 19 %.

Scolithus tubes are common. Winding burrows occur in a thin clay-laminated layer (126.9—126.8 m).

The bedding is not distinct. Dip angles of 5—10° were observed at several levels, but in the finely laminated parts the stratification is often practically horizontal. Only in the uppermost part of the section a few occasional high values were noticed. Cross-bedding was observed at a few levels.

Clay stratification had partly been disturbed by flowing sand (plunge structures). Thin clay layers were pierced by *Scolithus* tubes (Plate I, Figs. 3—4).

Mud-cracks occur at one level in the upper part of the section.

The curve of the median diameter oscillates comparatively little and runs almost invariably between the limits of 100 and 200 μ; the level 124 m, however, forms an exception with a low value (65 μ), but a sample somewhat below the exact 124 m level showed a median diameter of 166 μ which corresponds to that of the bulk of the samples. Particles of the fraction 2—1 mm occur sporadically in very small quantities (0.04—0.06 %). The fraction 1 mm —500 μ is also represented by small amounts; omitting a single value of 8.5 % (128 m), the average frequency is 0.5 %. The frequency of the fraction 500—250 μ largely increases up to 128 m and decreases thereafter (mean for the section 18.6 %). The fraction 250—125 μ dominates strongly (mean for the section 45.3 %); however, the curve has a general tendency to fall after an initial rapid rise. The frequency of the fractions 125—60 μ and 60—20 μ is comparatively high in the bottom and top parts but somewhat lower in the intervening portion; particles smaller than 20 μ are few, except in the top (mean values: 125—60 μ = 24.2 %; 60—20 μ = 5.2 %; $<$ 20 μ = 2.8 %).

The sorting is good; the curve of the coefficient of sorting oscillates around 1.5 with small amplitude, except at the level of 124 m where the coefficient is exceedingly high (3.6).

Smaller quartz particles are often secondarily enlarged by recrystallization, especially in *Scolithus* tubes.

Inconsiderable quantities of minute weathered feldspar grains were observed in the disintegrated samples. They are generally angular. Small amounts of mica also occur; they appear in somewhat greater abundance in the thin clayey strata, generally as extremely thin flakes.

Chlorite-like and glauconite-like substances were seen only in a few samples. Phosphoritic nodules were not observed but very small quantities of phosphorus were noticed in the analyses at the lower and upper boundaries (0.01—0.03 %); phosphorus was not proved in the remaining part of the section, except one level, viz. 129.5 m (0.01 %). Scattered pyrite crystals were found practically throughout the section, viz. from the 133 m level. They are often associated with greyish-green clay and kaolin-like matter. Enclosures of these components are sometimes surrounded with pyrite crystals. Pyrites also occur in *Scolithus* tubes, often along the walls. The quantities of sulphur proved in the analyses are small. From 128.5 m to 127.5 m only traces were found and then the maximum frequency amounts to 0.14 %. Well-rounded brownish tourmaline grains are comparatively abundant. Garnet crystals appear at several levels. Asphalt-like nodules and fragments of them were found in a few samples; they were, for instance, noticed in a *Scolithus* tube at 133 m. A small quantity of a graphite-like substance is enclosed among an aggregate of quartz crystals at 125.1 m. No carbonaceous substances were observed in the analyses. Slight traces of calcareous substances were found at one level (125.9 m). An analysis of a sandstone sample from 128.05 m with regard to fluorine indicated 0.127 parts per thousand.

The iron content is mostly low and rather constant (0.64—1.43 %). One higher value was noticed in the bottom part. The curve increases continuously in the uppermost part of the section.

The radioactivity diminishes in the lower part of the section and is very low or none in the middle (maximum 3 impulses in the portion 131—125.5 m). Above 125.5 m the tendency is mainly rising.

No fossils were observed, but their presence is indicated in different ways, viz. by *Scolithus* tubes and at one level irregular burrows, asphalt-like and graphite-like substances, as well as pyrite.

IV. 124—122.6 m. This section is developed as greyish-green "crow rock" very similar to section II.

The fine lamination of greenish-grey clay substances is irregular, partly owing to irregularly winding tubes.

The porosity is distinctly higher in the lower part of the section.

The granulometrical data are of about the same order of size as in the underlying section.

Part of the quartz particles are coated with secondary crystals, especially in the burrows.

Feldspar, mica, chlorite-like and glauconite-like substances, pyrite and tourmaline occur in very small quantities. The sulphur frequency is only 0.06—0.12 %. Phosphoritic nodules were not observed and no phosphorus was noticed in the analyses except at the lower boundary (0.03 %). Carbonaceous substances were not found in the analyses but small quantities of bituminous substances (partly asphalt-like nodules) and graphite-like matter appear in aggregates of recrystallized quartz. A thin stratum at 123.3 m is calciferous.

The increase in frequency of iron noticed in the upper part of the underlying section continues and the curve attains a maximum of 6.0 % in the upper part of the present section.

The gamma radiation gradually descends to zero within this section.

Fossils were not observed, but the presence of organisms is indicated by winding tubes, pyrite, bituminous substances, and graphite-like matter.

V. 122.6—109.7 m. This section consists of alternating layers of dark-green shale and sandstone. The rock is well consolidated. Parts of the shale are homogeneous by naked eye inspection, parts are clearly micro-stratified with light-coloured coarser sediments. The sandstone layers are stratified to a great extent with clay substances (micro-strata) and glauconite. Clay lumps appear at the bottom of the section but are very few elsewhere; one of the latter consists of kaolin-like matter.

In the lowermost part of the section the porosity soon descends to low values (9—12.5 % at 121.5—120.5 m), but thereafter (up to 114.5 m) the tendency is chiefly rising. Above this level some considerable fluctuations occur (from 11 to 30.5 %).

The bedding in glauconite-stratified sandstone is very distinct, generally parallel and gently dipping; cross-lamination occurs only occasionally. The fine stratification of dark green clay substances is equally distinct and to a great extent parallel, but many irregularities appear, developed mainly when semiliquid clay layers were buried by sand flows. Scour and fill structures with distinct clay lamination also occur. Transition between sandstone and shale is gradual or sharp, the latter particularly when sandstone is overlain by shale. Dislocations in the consolidated rock are negligible.

Structures other than beddings are abundant and generally distinct. The most remarkable among them are ptygmatized fillings of mud-cracks in the upper part of the section. They have been pushed laterally to a great extent, obviously before the sediment was definitely consolidated (Plate I, Fig. 2). In this part of the section are also dragging trails. Excellent flow and plunge marks occur in the lower part of the section (Plate I, Fig. 1). A few structures interpreted as swash marks were observed in and below the ptygmatized portion and minute interference ripples were found in the lower part of the section. Short cuneiform elevations appear on surfaces in different parts of the section. Mainly horizontal burrows were observed at a few levels chiefly in its middle part.

Most of the data of the median diameter fall between the limits of 10 and 20 μ; in the portion 119—117 m the median diameter is about 30 μ.

No particles larger than 125 μ were noticed in the analyses below 120 m, but such occur at the very bottom, as observed in the binocular inspection of the core. Above the 120 m level particles larger than 125 μ appear in small numbers (average values: 1 mm—500 μ = traces; 500—250 μ = 0.2 %; 250—125 μ = 2.4 %). The fraction 125—60 μ is moderately abundant, average 10.3 %. The fractions 60—20 μ and $< 20\ \mu$ dominate; the average frequency of the former for the whole section is 33.5 % and that of the latter 55 % (max. 81 %).

The sorting is not good; below 120 m the coefficient mounts from 1.75 to 1.86 and above the 120 m level the curve largely oscillates between 2 and 2.5.

The quartz particles have grown to some extent by secondary crystallization.

Small and generally angular grains of microcline (for the most part weathered) appear in small quantities in the disaggregated samples; one big weathered crystal of potassium feldspar was noticed at the very bottom of the section in the binocular inspection of the core. Mica is poorly represented throughout the section.

Tourmaline grains occur in many samples, but the frequency is very low. Garnet crystals were observed in a few samples, and part of a slickenside is covered with galena.

Small pyrite crystals appear throughout the section; the frequency is greatest somewhat above the midheight. In the lower third of the section the sulphur content is about the same as in the underlying section, but in the upper two thirds it is on the average much higher but fluctuates strongly (max. 0.74 %, min. 0.12 %). Asphalt-like nodules were observed in the binocular inspection only at a few levels; carbonaceous substances did not show up in the chemical analyses except at 118 m and 121.55 m (0.04 %).

Glauconite suddenly became an important constituent in quantitative respect in this section. It appears with comparatively small amounts in its bottom-most part but the frequency increased rapidly; in the upper part, on the other hand, it is low again. The glauconite grains are small and generally of a fairly loose texture. They are distinctive of the sandstone layers, where they constitute an essential component. When present in the shale layers, they mainly occur in the intercalated light-coloured thin strata of somewhat coarser materials and only to a subordinate extent in the shale substance. The glauconite grains in the light-coloured thin strata are generally larger than the accompanying quartz grains.

Phosphoritic nodules are characteristic constituents among the members which appear at the very bottom of the section. The phosphorus curve begins with a considerable maximum (0.8 %). Thereafter, the frequency is moderate and little fluctuating (0.04—0.14 %), except in the upper part (0.03—0.3 %).

Calcium carbonate is another of these characteristic members with highest frequency at the very bottom of the section (20.7 %). It occurs as thin strata and sometimes as irregular intercalations in a great many sandstone layers throughout the section but is not present in pure shale. The frequency is greatest at levels with comparatively coarse, rounded quartz grains, as in the bottom-most part of the section. It accompanies the glauconite to a great extent.

Kaolin-like dust is often disseminated in the sandstone strata.

The average iron content is high but the curve fluctuates strongly in the lower two thirds of the section (1.86—7.72 %). Iron is also abundant in the upper third but the amplitudes of the changes in frequency are smaller (3.07—5.21 %). The chlorine content in a greenish-grey shale layer at 120.5 m was 0.27 %.

At the lower boundary of this section the radioactivity is none, but increases rapidly to comparatively high values (16 impulses at 120 m). In its continuation the curve runs for the most part between the limits of 10 and 17 impulses (a few occasional lower values observed).

True fossils appear for the first time in this section, viz. *Discinella holsti* MOBERG in the bottom part and a single specimen of *Volborthella conica* SCHINDEWOLF somewhat above the midheight. Minute flat-rounded fragments of fossils occur in the uppermost part of the section. One specimen of the silicious microfossil, so common in the Middle Cambrian sequence of the core (arenaceous foraminifera, according to WÆRN, 1952), was also observed there. It is striking that burrows and trails of animals are practically absent in the section.

VI. 109.7—90.75 m. This section chiefly consists of white sandstone, at some levels laminated by greyish-green clay, kaolin-like substances, and glauconite. Fine laminations of greyish-green clay very similar to those which are characteristic of the underlying section occur at some levels in the lower part of the section. Dark clay substances constitute thin layers in fairly coarse sandstone both in the bottom-most part of the section and, particularly, in its upper part. Some of them have cracked. One portion in about the middle of the section (102.5—101.6 m) is distinguished by irregular clay laminations and irregular vertical burrows. The lamination immediately below this portion is even more irregular but burrows are not present. Enclosures of greyish-green clay and kaolin-like substances are characteristic of the section.

The rock is partly poorly consolidated in the portion 100—92.5 m, and both coarse-grained and fine-grained sandstones can be crumbled with the fingers. The greatest loss of core in the drilling occurred in this portion. The consolidation is better in the under- and overlying parts of the section, where the rock is only occasionally so loose that it can be crumbled between the fingers.

The porosity is on the average highest in this section (about 30 % in a great part of it). Fluctuations are mostly fairly small. They are considerable only at a few levels in the lower part of the section where comparatively low values appear (about 15—20 %).

The bedding is mostly rather clearly discernible. Cross-bedding is common, especially in the fairly coarse-grained white sandstone in the upper part of the section. Great angles of bedding are common (sometimes 20—30° with the horizon); in the lower part of the section the bedding is also sometimes practically horizontal.

Plunge structures owing to sand flow, and scour and fill structures occur at clayey levels in the lower part of the section. Small primary slides are registered in the very irregularly laminated zone immediately below the above-mentioned burrowed portion.

Surface structures are present mainly in the lowermost third of the section and in its uppermost part; they are very few in the intervening fairly coarse sandstone. Mud-cracks are common both in the lower and topmost parts of the section, and in the lower their fillings are sometimes ptygmatized. As indicated above, some of the dark clay laminations in the fairly coarse sandstone also are sun-cracked. Small cuneiform elevations and a few mainly horizontal structures, probably produced by animals, were also noticed.

The median diameter varies much below the 105 m level (max. 165 μ, min. 11 μ). Complementary analyses at a few centimetres distance from the exact metre levels of 106 m and 108 m where low values appear showed the same order of size as the samples above 105 m (106 m: 105 μ; 108 m: 108 μ). Above 105 m the curve runs largely between the limits of 100 and 300—400 μ, except for the level of 96 m (84 μ). Considering the whole section, the larger fractions have increased somewhat compared with the previous section: 2—1 mm = traces; 1 mm—500 μ = average 0.8 % (0.01—3.4 %); 500—250 μ = average 18.3 % (general increase upwards under strong fluctuations); 250—125 μ = average 34.1 % (strongly fluctuating but dominating fraction in the upper part of the section). The mean of the fraction 125—60 μ is fairly high (27.3 %), but the frequency varies considerably (4.8—80 %). The fraction 60—20 μ decreases in frequency upwards, and above 101 m the values are mostly very low (mean for the whole section 7.3 %). The curve of the fraction < 20 μ fluctuates much in the lower part (0.5—68 %) but above 101 m the frequency is invariably very low.

The sorting is mostly good but varies much in the lower part of the section, and poor sorting was noticed there at some levels (108 m: 2.8; 106 m: 2.7). Above 101 m the fluctuations are small (1.27—1.38; at 92 m the coefficient is somewhat higher: 1.52).

The grains in the larger size grades are generally well rounded, but the small particles are mostly angular. In the lower part of the section it occurs that thin layers consisting exclusively of well-rounded quartz grains are included among clayey strata, and in the middle part it was observed that a thin calcareous layer is crowded with rounded quartz grains. The rounded grains are often dark-coloured. The quartz grains, even larger ones, are to some extent coated with secondary crystals at some levels.

Weathered and for the most part angular small grains of microcline appear in very restricted quantities in most of the samples. Mica, occurring mostly as extremely thin flakes in argillaceous layers, is largely restricted to the lowermost third of the section.

Brownish, well-rounded tourmaline grains are comparatively abundant in the fraction 125—60 μ in most of the samples; no tourmaline was, however, found in the samples 106—105 m. Garnet crystals were observed in a few samples in the lowermost third of the section. A minute occurrence of galena was found in its top.

Glauconite is present chiefly in the lowermost third of the section, though in rather low frequencies; only in sandstone strata around 105 m is it somewhat more common. In the remaining part of the section single grains of glauconite were noticed. Larger phosphoritic nodules are distinctive of two levels, viz. the bottom-most part and one level in the middle of the section (101.7—101.5 m). Phosphorus was indicated in the analyses only in the lowermost third of the section and in its top. The frequency in the former is low: 0.01—0.04 %, except for the portion 106—104.5 where it is somewhat higher (0.08—0.10 %). The highest phosphorus value of the stratal sequence was observed in the top, viz. 2.6 % (92 m). Minute pyrite crystals generally appear in small quantities; they are very rare in fairly coarse-grained sandstone in the upper part of the section. The average frequency of sulphur is low (less than 0.1 %) and fluctuations are comparatively small, but higher values and greater fluctuations appear in the top (maximum at 92.5 m: 0.83 %). Carbonaceous substances showed up at 91 m in the analyses and asphalt-like nodules were observed in the two lowest samples in the section and impregnations of bituminous substances characterize the very top of the section.

Kaolin-like dust occurs in the sandstone, but the frequency is low in coarser and more recrystallized layers.

Calcareous substances are rather abundant in several parts of the lower half and in the topmost part of the section, but they are practically lacking in the intervening fairly coarse-grained sandstone. This also appears from the chemical analyses; calcium carbonate was proved at the following levels: 108.5 m (8.5 %), 101.5 m (21.2 %), 92 m (21.5 %), and 91 m (22.0 %). Higher frequences are often associated with phosphoritic nodules and greater amounts of larger rounded quartz grains.

The frequency of iron is mostly low and fairly constant (for the greater part about 0.5—1.0 %). Higher amounts appear in the portion 106.5—104.5 m (maximum 3.6 %) and at 92.5 m (5.94 %).

The potassium content in a sample from a thin shale stratum at 104.5 m is 5.80 %.

The radioactivity is mostly low, for the greater part only 1—3 impulses, and at some levels there is none. A few high values were noticed, the most conspicuous in the portion 106—104.5 m (maximum 21 impulses).

Torellella laevigata (LINNARSSON) is rather abundant at several levels in the fairly coarse-grained sandstone in the upper part of the section. Specimens of the silicious microfossil were observed at 105 m. Flat-rounded fragments of fossils occur at several levels.

VII. 90.75—84.11 m. This section consists of fine-grained white sandstone with abundant laminations of generally dark clay substances, except a few thin layers and the uppermost half metre which is a pure sandstone impregnated with bituminous matter. The top surface is deeply corroded.

Consolidation is good throughout the section.

The porosity has diminished somewhat compared with the underlying section. It fluctuates rather strongly; the curve oscillates mainly between the limits of 10 and 20 %.

Bedding and other internal structures are exceedingly distinct in the white sandstone owing to the clay lamination (Plate III, Figs. 2—3; Plate IV, Figs. 1—2); fine laminations of white fine-sand or silt in thin shale strata also contribute to indicate internal structures. The argillaceous lamination is to a great extent irregular or tortuous and mostly anastomosing, but it is also in part straight or gently curved; this is generally true for the laminations of finesand and silt in thin shale strata. The bedding is sometimes horizontal or practically so, and the maximum angles of bedding are mostly moderate (about 10°, in a few cases about 15°).

Transitions from sandstone to shaly layers are often gradual by increasing lamination, but can also be abrupt. Transitions in opposite direction can be sharp or gradual via fading lamination but are most often irregular. Sack-like depressions have often developed on the upper surfaces of shaly strata; these structures were apparently caused by sandflow over unconsolidated mud. Thin sand layers and mainly horizontal linguiform enclosures have been pushed into mud beds as well as horizontal, mostly vertically somewhat compressed strings of sandstone. Structures indicating turbulent movements are sometimes discernible in the transverse sections.

Mud-cracks with generally ptygmatized fillings are fairly abundant in the upper half of the section, except the bituminous uppermost half metre and the very top of the laminated rock.

More or less irregular horizontal burrows and sinuous horizontal grooves made by animals occur at several levels. Some cuneiform elevations were also noticed.

The median diameter of particles largely increases upwards from 21 μ to 78 μ. Particles of the fraction 500—250 μ are very few. The frequency of the fraction 250—125 μ is low (2--5 %). The fractions 125—60 μ, 60—20 μ, and < 20 μ predominate (mean 36.3 %, 29.8 %, and 33 %, resp.; the frequency of the former increases, that of the second is largely uniform, whereas that of the third decreases upwards).

The sorting is comparatively poor, but there is a marked tendency of better sorting upwards in the section (from 3.0 at 89 m to 1.8 at 85 m).

The majority of the quartz grains are small and angular, but the few larger grains present are rounded.

Mostly angular small grains of weathered microcline occur in minute quantities in practically all samples. Mica flakes are common on bedding planes of shales. Tourmaline grains appear occasionally. Single glauconite grains and small pyrite crystals were found practically throughout the section. The frequency of sulphur is fairly constant within each of the following two portions 90—87 m (0.35—0.41 %) and 86—84.5 m (0.12—0.15 %). These portions are separated by a distinct maximum (0.86 %). Phosphoritic nodules were not observed. The phosphorus content is invariably low (0—0.07 %); the 0-values appear in the upper part of the section. Carbonaceous substances are the cause of the brownish colour of the beds in its top, where a frequency of 1.26 % was found at 84.45 m. A few larger irregular lumps of asphalt-like substances were noticed there and single minute nodules of this material are also present at lower levels. Calcareous substances occur at several levels, partly rather abundantly, so that strata of calcareous sandstone of up to about 5 cm thickness have developed. Calcium carbonate was proved in the chemical analyses only in the very top of the section (84.5 m: 4.3 %). A thin bed of calcareous sandstone at 86.4—86.3 m was analysed separately and a content of 33.1 % was found.

On an average, the iron content is much higher than in the underlying section, but fluctuations are very strong (min. 1.08 %, max. 6.85%).

The chlorine content in a greenish-grey shale at 89.5 m is 0.18 %.

The radioactivity fluctuates considerably (min. 3, max. 16 impulses). The frequency is for the most part less than 10 impulses but in the portion 90.5—88 m the curve runs between the limits of 11 and 16 impulses.

Volborthella tenuis F. SCHMIDT, occurring at three levels in the bottom part of the section, is its only true fossil. The specimens appear in a great number at the two upper of these levels where they had obviously drifted together rapidly.

Middle Cambrian

The Middle Cambrian part comprises the division 84.11—40.9 m and is thus 43.2 m. The main component is a greyish-green and dark green clay shale, to a great extent interstratified with thin layers of light colour and larger grain size. A great many of the interstratified layers are calciferous. Fossils occur throughout the stratal sequence: the lower half is characterized by brachiopods and the upper by trilobites. The sequence begins with a thin conglomeratic layer and is limited against the overlying Ordovician by another such layer. It can be divided lithologically into two sections with the aforementioned types of faunas.

The lower section rests upon the deeply corroded Lower Cambrian top surface. The separating thin conglomerate (Plate IV, Fig. 3) includes slabs of the topmost Lower Cambrian bituminous sandstone, large phosphoritic nodules (up to about 1 cm diameter), greenish-grey clay lumps, and rounded quartz grains of moderate size. The matrix is rich in glauconite, and also kaolin-like substances and calcium carbonate are present.

VIII. 84.11—about 60 m. The shale substance is greyish-green, sometimes dark green, and black. The black shale is predominant in the portion 79.5—78.6 m; single layers of black shale occur up to 76 m. The shale is interstratified with thin beds and laminations of light-coloured coarser particles. These beds are to a great extent impregnated with bituminous substances.

The rock is well consolidated throughout. The general falling tendency in porosity in the underlying section continues up to 74.5 m where only 4 % was noticed. Here the porosity begins to increase gradually, and in the upper half of the section the curve runs for the most part within the limits of 10 and 15 %.

The stratification is marked not only by the above-mentioned thin beds and laminations of comparatively coarse-grained materials in shales and vice versa but within the shales it is also apparent because of different shades of colour.

The bedding is horizontal or gently dipping (maximum angles with the horizon most often 2—3°). Greater angles appear occasionally, viz. within the intercalating coarser strata.

Various structures indicating movements in the water and the sediment during the accumulation were observed. Among them are small concavities developed in the top surface of unconsolidated mud when overflown by suspensions of coarser materials. Moreover, arenaceous and silty beds have been pushed into the mud; some of them are short and foliate, others are short and thick and chiefly lenticular in transverse section. Scour and fill structures were noticed at some levels. Flow structures in mud have been preserved throughout the section. Generally broad and flat ripple structures occur in several thicker arenaceous strata.

Mud-cracks were noticed in the very top of the section. Tiny ridges interpreted as swash marks appear in its lower half. Dragging trails occur at the bottom of the section. Small straight elevations and slightly curved or sinuous trails certainly made by animals appear in some silty strata. Vertical burrows do not occur in the section.

The curve of the median diameter most often runs between the limits of 10 and 20 μ, but at some levels, particularly at the bottom and in the upper part, also somewhat higher values occur. Size grades larger than 125 μ play a subordinate rôle: the fraction 250—125 μ is weakly represented throughout the section and larger size grades appear sporadically, even the fraction 2—1 mm. The average frequency of the fraction 125—60 μ is 12.4 %; in the middle part (75—67 m) the values are on the average smaller than in the overlying and underlying portions of the section. Particles 60—20 μ are abundant (mean 37.8 %) and those smaller than 20 μ dominate (mean 50 %).

The sorting is poor in the lowermost part (coefficient mostly about 2.5—3; max. 3.73); in the remaining part it is somewhat better, coefficient mostly about 2 (min. 1.55, max. 2.55).

The majority of the quartz grains are small and angular. Larger grains occurring in small quantities are generally rounded. Somewhat greater quantities of larger rounded grains were noticed in the binocular examination at some levels in the lower part of the section where they occur together with glauconite, calcareous substances, phosphoritic matter, and fragments of brachiopods.

Generally angular minute grains of weathered microcline were found in very small quantities in most of the samples. Mica flakes are common on shale surfaces. Single small rounded tourmaline grains of brownish colour (often smaller than 60 μ) appear in most of the disintegrated samples in the upper half of the section and occasionally in the lower half. A few fragments of garnet crystals were noticed at some levels in the lower part of the section. Fairly large aggregates of pyrite crystals occur at several levels; they are most frequent in the lower part of the section. The average content of sulphur is very high but the curve oscillates heavily (max. 1.14 %, min. 0.09 %). The general tendency is falling from the bottom up to about the midheight (fall from highest maximum to lowest minimum of the section). Thereafter the general tendency is rising under very strong fluctuations up to 66.5 m, again largely followed by decrease.

Glauconite is very abundant just above the basal conglomeratic layer, and the rock is dark green of layered glauconite. This stratum is thin (cf. Plate IV, Fig. 3). It is sharply limited by a very dark shale at 84.0 m. Glauconite is also present in intercalating arenaceous strata at higher levels, but occurs in greater frequencies mainly within the portion 79.4—about 77 m.

Calcareous substances are present at a great many arenaceous levels throughout the section. In the chemical analyses a frequency of 10 % was found at 72.5 m.

The phosphorus frequency is low and uniform; with few exceptions the curve runs between the limits of 0.05 and 0.10 % (high values around 79—80 m). Carbonaceous substances are included in the shale substance and, except for the bottom-most and topmost parts of the section, also in brown-coloured somewhat coarser thin intercalations, but the quantities are generally small. The greatest frequency in the shale substance occurs in the lowermost ten metres, especially in the portion 79.5—78.6 m, where a maximum of 1.14 % was noticed; in the remaining part of the ten metres division the frequency is below 0.5 %. In the overlying part of the section the frequency is generally lower than 0.1 %. Asphalt-like substances were noticed in the disintegrated samples in its lower part (up to about 77 m); minute nodules appear rather constantly below the 80 m-level, but only occasionally higher up.

The iron frequency is high and fluctuations are moderate for the greater part. The curve of "total iron" mostly runs between the approximate limits of 5.5 % and 7.5 %, and ascending and descending tendencies of the curve are often fairly extensive. Some lower values were noticed in the bottom part of the section, and in the top (61.5 m) is a very high value (7.93 %) from where the curve falls successively towards the upper limit of the section.

The potassium content in shale at 73.20 m is 3.83 % and the fluorine content at 74.2 m is 0.154 parts per thousand.

The radioactivity is comparatively high and varies moderately. For the greater part the curve oscillates between the limits of 10 and 15 impulses. At some levels the frequency is somewhat higher (maximum 18 impulses).

Many fragmentary shells of brachiopods are enriched throughout the section in the thin arenaceous strata. The majority of the identifiable shells are referable to *Acrothele granulata* LINNARSSON. Flat-rounded fragments of brachiopods are abundant in the lower part of the section, but they also appear at some higher levels. Silicious microfossils occur throughout the section.

IX. About 60—40.9 m. The main substance of this section is greenish shale rich in fossils. Arenaceous or silty laminations are of subordinate importance, but the uppermost part of the section is somewhat arenaceous. Impregnations of bituminous substances are restricted to this layer.

The consolidation is on the whole good, but the rock is fairly loose in some argillaceous layers, especially in the upper part of the section. Porosity fluctuates greatly with lowest values around 10 % (minimum 7.5 %) and highest between 20 and 25 %. The majority of the values amount to 10—20 %.

The bedding is generally horizontal or forms only small angles with the horizon. A few larger angles (10—20°) were noticed, generally in arenaceous and calcareous strata. Flow structures in mud were observed throughout the section, except for two portions where they are absent or very scarce (about 60—57 m and about 54—52 m).

Surface marks were found only in the upper part of the section, particularly in the arenaceous layer in the top. Here occur mud-cracks, structures which may be foam-marks, crescent-shaped excavations, dragging trails, and ripple structures. Tracks of organisms are extremely rare and were noticed only at 45.5 m.

Short vertical structures (probably burrows) occur in the upper part of the section (about 44.5—42 m) and at 50.9 m. They are about 1 cm high, spool-shaped, and filled with pyrite aggregates. A horizontal burrow was observed at 41.5 m.

The median diameter is on the average smaller than in the other sections; the curve runs for the most part between the limits of about 10 and 15 μ. Particles larger than 125 μ are few and among them the fraction 250—125 μ is the most abundant with a maximum of 1.5 % in the bottom of the section (59 m). Only single particles of the size grade 1 mm—250 μ were observed. The average frequency of the fraction 125—60 μ is 3.2 %; it is abundant at the transition from the previous section, but thereafter the amounts are small, particularly in the portion 48—44 m; however, there is a final increase in the top of the section. The fractions 60—20 μ and < 20 μ have a fairly constant frequency throughout: average 34.6 % and 62 %, resp.; the latter is the highest average value of this fraction in the whole stratal sequence.

The sorting is for the most part rather uniform, the curve generally running between the limits of 2 and 2.5. Better sorting was noticed at two levels; one of them is that of 59 m.

The majority of the quartz grains are small and angular. The few larger grains present are mostly rounded. A considerable part of the particles of the 59 m level are strikingly well-rounded. A limestone bed at 42.5 m also includes a noticeable quantity of rounded quartz grains.

Feldspar grains are few, appearing chiefly in the lower half of the section. Mica also is scarce. Single well-rounded minute tourmaline grains were noticed in a few samples in the middle and lower parts of the section. A few fragments of garnet crystals were found at the 48 m level.

Glauconite occurs throughout the section, though mostly in small quantities. The highest frequencies are in the lower part of the section, particularly at the 59 m level. The glauconite particles generally appear in strata of larger grain size, but may occasionally be present also in pure shale.

Phosphoritic nodules were not found. The phosphorus curve is highly constant in the lower two thirds (about 0.05 %), but it fluctuates rather considerably in the upper third. Large pyrite aggregates occur at several levels throughout the section; very large aggregates appear in great quantities in the uppermost part of the shale (about 44.5—42 m). Exceedingly fine crystals can be seen here, especially at the 44 m level. The pyrite crystals and aggregates have been worn at several levels; such were observed at 57, 54, 47, 45, 43, and 41 m. As mentioned above, short spool-shaped tubes are filled with pyrite. The highest sulphur values of the stratal sequence were noticed in the uppermost part of the section (maximum 3.12 %). In its remaining part most of the curve runs with comparatively gentle fluctuations between the limits of 0.25 and 0.55 %. The curve exhibits a rather continuous increase from the 53.5 m level up to the portion with the very high values. Galena was noticed in the very top of the section.

Thin beds of impure limestone (maximum 10—20 cm thick) occur at several levels, and insignificant calcareous strata appear in the intervening portions. The content of calcium carbonate in two limestone beds is 36.3 % and 55.2 % (59.5 m and 52.5 m, resp.). Vertical prisms of calcite have developed in one bed (42.5—45.4 m). Trilobite shells are included in many of the upper beds, sometimes in great quantities.

Carbonaceous substances are present in small quantities; the frequency is generally lower than 0.1 %. It is higher in the bituminous arenaceous stratum in the very top: at 42 m it is 0.40 % and at 41.5 m 0.54 %.

The potassium content in shale at 50.25 m is 2.48 %, the chlorine content at 58.5 m 0.23 %, and the fluorine content at 47.75 m 0.139 parts per thousand.

The iron content is high; the curve runs for the most part between the limits of about 4.5 and 6 %. The decrease in frequency in the uppermost part of the underlying section continues up to 58.5 m but thereafter the frequency is fairly constant (4.86—5.75 %) up to 53 m where more pronounced changes appear. The subsequent general tendency of the curve is falling. The occasional high frequency in the top is due to redeposited pyrite crystals.

The radioactivity is of about the same order of magnitude as in the previous section. Fluctuations are also mostly moderate, but a few comparatively low values (minimum 8 impulses) occur in the lower part of the section; in the upper part the radioactivity shows a continuous decrease to 4 impulses just below the Ordovician black shale.

Trilobites are predominant among the abundant fossils, viz. *Ellipsocephalus polytomus* LINNARSSON, *Paradoxides* species, and Agnostids. Mr. WÆRN also noticed *Hyolithes* specimens and brachiopods of the same genera and partly of the same species as in the underlying section. Flat-rounded fragments mainly of trilobite shells occur practically throughout the section. Silicious microfossils (cf. WÆRN, 1952) were observed at several levels.

Basal Ordovician.

Black shale (Ceratopyge alum shale) and transitional layers from this one to the overlying Planilimbata limestone are considered here. Analyses of the overlying Ordovician limestone are summarized at the end (p. 73).

Black shale. This layer is 2.8 m thick (41.9—39.1 m). It is separated from the underlying Oelandicus shale by a thin conglomerate (Plate IV, Fig. 4). The most important components of the conglomerate are flat pebbles of maximally a few centimetres length consisting of light greyish, fine-grained sandstone. Lumps of pyrite are included. The conglomerate is traversed by mainly horizontal anastomosing fissures filled with calcite. The matrix of the conglomerate is shale substance, greyish-green in the lower part and darker in the upper. *Obolus apollinis* EICHWALD is reported from the conglomerate (WÆRN, 1952).

The black shale is fairly uniform throughout. Minute laminations were traced in the lowermost part. Two horizons with stinkstone are included in the shale, one in the middle part (4.5 cm thick) and the other in the top (9—10 cm). The calcite crystals are for the most part larger in the upper stratum. The frequency of calcareous substances increases upwards in this layer from 8 % to 58 % (Fig. 1). Horizontal and short vertical burrows at about 40 m and 39.5 m are filled with pyrite; pyrite also constitutes thin horizontal beds. The sulphur content in the black shale is high (max. 1.7 %). The frequency of carbonaceous substances, diminishing slightly upwards, is also high (max. 6.95 %). Three samples were examined for oil and gaseous hydro-carbons: one from the bottom part (40.68—40.65 m), one from the middle (40.24—40.21 m), and one from the upper part (39.41—39.38 m). The following results were obtained (percentage values):

	Oil	Gas	Coke	Water
39.41—39.38 m ...	3.1	2.4	91.0	3.5
40.24—40.21 » ...	1.6	2.5	93.0	2.9
40.68—40.65 » ...	2.2	2.1	92.0	3.7
Mean	2.3	2.3	92.0	3.4

Extraction of oil from the black shale (41 m) by means of chloroform gave a result of 0.4 %.

The content of "total iron" varies between 4.45 % and 6.68 %, and the phosphorus content is moderate: max. 0.38 %. The frequency of potassium at 40 m is 4.75 %, that of chlorine at 40.5 m 0.09 % (the lowest value observed in the stratal sequence), and that of fluorine at 40.25 m 0.336 parts per thousand. Samples from some levels were analyzed for vanadium with the following results:

39.50 m — 0.12 %
40.00 » — 0.14 »
40.50 » — 0.19 »
40.72 » — 0.18 »
40.85 » — 0.23 »
Mean 0.19 »

This frequency is of the same order of magnitude as observed in previous analyses of Dictyonema shales from Öland (cf. WESTERGÅRD 1947. Fig. 1, p. 4).

The grain size was not examined, this rock being not disintegratable. The porosity is considerably lower than in the arenaceous strata in the top of the underlying section (decrease from 24—25 % to 9.5—13 %).

The radioactivity is higher than in any other part of the core. Maximum of 35 impulses was observed in the middle of the black shale.

Specimens of *Bröggeria salteri* (HOLL) and *Acrotreta* are reported by Mr. WÆRN.

Transitional layers (cf. Fig. 1). These layers are two. The lower one is 4—4.5 cm thick. Its matrix consists of greyish and greenish argillaceous matter crowded with large calcite crystals coated with bituminous substances. The matrix has been strongly squeezed by the growth of these crystals.

The upper layer (3—5 cm thick) is very rich in glauconite. It also contains lumps of greyish-green argillaceous matter similar to that of the underlying stratum, some phosphoritic nodules, large calcite crystals, and small pyrite crystals.

Above this layer follows greyish-green Planilimbata limestone.

The granulometry of the insoluble residue (exclusive of glauconite) was examined in three samples from the transitional layers. The median diameter is greatest in the glauconite layer (about 20 μ). Particles larger than 60 μ were present in noticeable quantities in all samples, particularly in the glauconite layer. They are least frequent in the limestone sample where particles of clay dimensions have the greatest frequency (about 37 %). The sorting is poor in all the three samples.

As appears from Fig. 1 the glauconite content increases heavily in the upper layer (about 54 %), and in connection with that also the iron content. The frequency of phosphorus and the radioactivity is likewise higher, but the frequencies of sulphur, carbonaceous substances and calcareous matter have decreased.

It was mentioned previously (p. 52) that other authors will describe the Ordovician limestone which extends up through the Ludibundus limestone of the Middle Ordovician. A few remarks will be made here about general trends of the curves continuing from the Cambrian portion.

The porosity curve runs for the most part between the limits of 10 and 15 %, but very low porosity was measured in the lower part of the section (minimum 2.5 %). The curve fluctuates more in the lower and upper parts than in the middle one where it is largely constant.

The curve of calcareous substances fluctuates considerably except for the portion 31—21.5 m. The frequency is here among the highest in the stratal sequence (lower half 92—95 %, upper on the average about 90 %). In the under- and overlying parts of the section the curve mostly runs between the limits of about 75 and 95 %. The latter limit is not surpassed but the former is transgressed at some levels. The most remarkable minimum appears

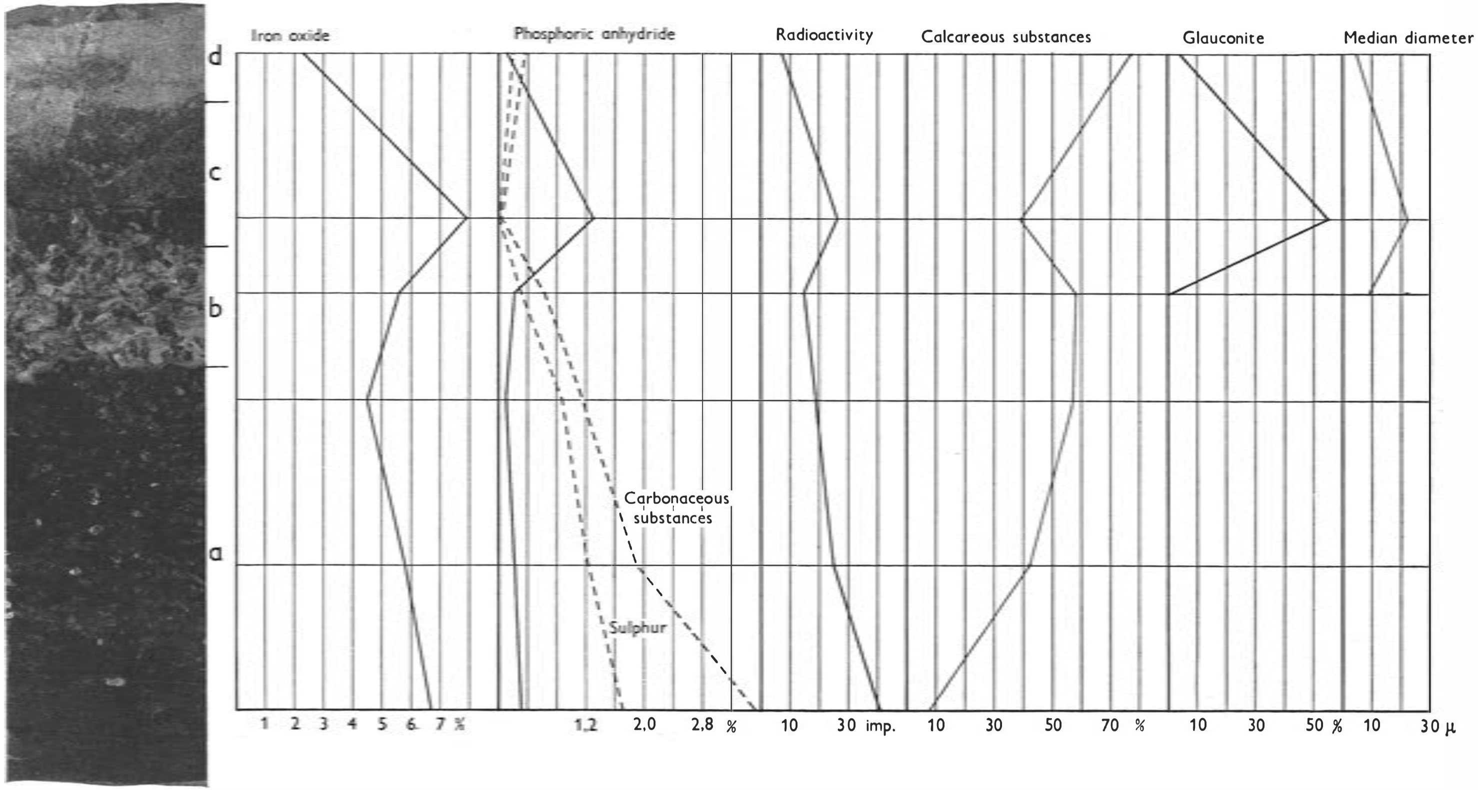


Fig. 1. Distribution of iron (given as oxide), phosphorus (given as phosphoric anhydride), carbonaceous substances, sulphur, radioactivity (impulses per minute), calcareous substances, and glauconite in the uppermost part of the black Ceratopyge shale (a), the overlying argillaceous (b) and glauconitic (c) layers as well as in the bottom-most part of the Planilimbata limestone (d). The median diameter is referable to insoluble residues of de-glauconitized samples. Core nearly $^{4}/_{10}$ of nat. size. Note the large calcite crystals.

at 38.5 m (26 %) and another noteworthy one at 31.5 m (55.8 %). The majority of the other minima falling below 75 % are situated between 20 and 11 m and are less pronounced.

The curve of "total" iron exhibits major fluctuations of considerable vertical extent within the limits of about 1 and 4 %. Most of the curve runs between the limits of about 1.5 and 3 %. Higher values occur occasionally; the most important appears at 31.5 m (6.84 %). The content of sulphur rapidly diminishes in the lowermost part from 0.35 to 0.02 % and remains low through the whole limestone layer. The frequency only occasionally exceeds 0.05 %, except for the uppermost part where somewhat higher values are more frequent. The average frequency of phosphorus is higher than in the Cambrian part of the core, but the curve fluctuates strongly (minimum 0.04 %, maximum 1.12 %). Apart from these fluctuations, the curve forms at least three main maxima separated by broad inflexions. These maxima are situated at the following levels: 31.5 m, 15 m, and 5.5 m. The content of carbonaceous substances is low throughout the limestone and fluctuates very little (generally 0.2—0.3 %; max. 0.5 %).

The radioactivity is mostly low; the main part of the curve does not rise beyond the value of 5. A smaller part of the curve oscillates between the values of 5 and 10, except for two levels where 12 and 13 impulses, resp., were measured.

V. Interpretation of environment and changes of level

Reconstructions of ancient environments and interpretations of lithogenesis and changes of level on the basis of single drill cores are impaired with more or less inevitable uncertainties owing to the fact that it cannot be taken for granted that the core is representative of the local development, no less of regional conditions. Uncertainty is reduced if exposures and other cores are available. It is necessary, for several reasons, to use the data obtained in the various analyses with care and discrimination. This is particularly true for the grain size which does not always represent the exact original composition of the sediment (cf. discussions in the preceding chapters dealing with environmental indications and methods of analyses). The fact must also be considered that every single sample may not be representative of the section from which it originates. Therefore, decisive importance should not be attached to the results of the analyses of a single sample, but the sequence of samples of which it is a member has to be examined as a whole.

Considering the aforementioned facts we may now proceed to discuss the local lithogenesis and changes of level as indicated by the present core.

This discussion may conveniently be preceded by an examination of the probable sources of materials.

A. Sources of material

One of the two core drillings on Öland which have pierced through the Cambrian finished in quartzite (WESTERGÅRD 1936) and the other (the present one) in granitic gneiss. The same types of rocks constitute the small islands in the sound of Kalmarsund; only a few of them are quartzitic, however. On the mainland W of the sound different types of granite (partly gneissic) predominate. Other important constituents are porphyries and rocks intermediate between these and granites. Basic rocks (mostly diorite and gabbro) are of subordinate frequency. Somewhat N of the sound the rock consists to a considerable extent of quartzite (the late Archaean Västervik quartzite formation). Smaller areas with quartzite also occur more to the south, inter alia in the vicinity of Kalmar; NE of this town is for instance the mainly quartzitic peninsula of Skägganäs. According to WESTERGÅRD (1936, p. 7), the quartzite of the Kalmar area and that revealed in the above-mentioned boring on Öland (Mossberga, just opposite Skägganäs) are probably the southernmost outlayers of the Västervik quartzite in the Kalmarsund area.

In our day, the Skägganäs quartzite and the quartzitic islands in the sound as well as the Mossberga quartzite form monadnocks (cf. WESTERGÅRD 1936, p. 11). The Mossberga quartzite "rises possibly almost 100 m above the granite surface in the neighbourhood" (l.c.). Following HEDSTRÖM and WIMAN (1906, p. 26), WESTERGÅRD gives reasons for the suggestion that this topography existed already at the initial transgression of the Cambrian sea. It can also be assumed that parts of the quartzite formation were broken down by the Cambrian sea, supplying material for the Cambrian sedimentation. WESTERGÅRD states that, at Mossberga, material had originated from a higher level of quartzite "somewhere in the vicinity of the boring" (op. cit. p. 11). HOLST (1893, p. 10) mentioned that pebbles of quartzite are included in erratic boulders of the Lower Cambrian basal conglomerate which are common in part of the Cambrian area on the mainland. The quartzitic formation seems to have been deeply weathered and may thus have been comparatively easily eroded; at Mossberga the uppermost 4.2 m of the quartzite are weathered. The unweathered quartzite is partly coarse and porous, and some layers are rich in mica and feldspar (WESTERGÅRD 1936, p. 5 f.). In the Västervik area, the quartzite formation is, likewise, of varying composition. It is chiefly strongly recrystallized quartzite, but feldspar-bearing sandstones are also present (cf. DU RIETZ 1949, p. 92). Some varieties of the quartzite are more or less rich in other minerals, especially mica and feldspar. Rounded quartz grains have sometimes been observed in the quartzite (SVENONIUS 1914, p. 47) but the majority of the grains are angular and irregular in shape. SVENONIUS (1905, p. 10 f.) measured quartz grains in different types of Västervik quartzite and found that the diameter mostly varies between 0.2 and 0.7 mm (sometimes the grains are 2—3 mm in diameter). Tourmaline is a very typical constituent among the accessory minerals in the Västervik quartzite. Calcite can occur in small quantities (SVENONIUS 1907, p. 10).

The granite and allied rocks are the other presumable source of materials. As mentioned above, they are of widely different composition. Their quartz grains are also of various appearance: in some granites blueish, in others white, and in a third type greyish or smoke-brown. These latter are rounded and drop-like (SVEDMARK 1904, p. 16). They occur in the so-called Götemar granite, which is of *rapakivi* type and which appears in a small area on the mainland chiefly opposite northern Öland and on the island of Jungfrun situated in the middle of the sound and at about the same latitude as the site of the present boring. The quartz grains in the other quartz-bearing rocks in the Kalmarsund area are irregular and angular. Concerning further components, it may only be mentioned that mica is often transformed into chlorite-like minerals and that tourmaline does not belong to the prominent accessory minerals as in the Västervik quartzite. Calcite may occur in small quantities (HEDSTRÖM and WIMAN 1906, p. 19). At the Cambrian transgression the granitic rocks were deeply weathered, which also appears from the present core.

It is beyond the scope of the present investigation to trace in detail the sources of the sediments in the core. Attention is only called to the fact that the Cambrian sediments may be derived not only from the granites and allied rocks but also from the quartzites of the Kalmarsund area. This conception is supported by the fairly abundant occurrence of tourmaline grains in the sandstone sections. For our purpose it was of special importance to have some information on the roundness of the quartz grains in the parent rocks for comparison with that of the grains in the Cambrian sequence of strata. It is evident that the good roundness of the grains in a great deal of the Cambrian sandstone has been achieved mainly by wear and reworking after their liberation from the parent rock.

B. Environment and changes of level

Two great stratigraphical gaps are included in the stratal sequence investigated here. One of them comprises the uppermost part of the Lower Cambrian, the other the later part of the Middle Cambrian and the whole Upper Cambrian with the result that the Ordovician Ceratopyge alum shale rests directly upon the Middle Cambrian Oelandicus shale. Therefore, the Cambrian and Ordovician divisions are treated separately below.

The Cambrian

The general course in the process of sedimentation was progressive, inasmuch as particles of smaller size largely increase in frequency upwards in the stratal sequence. This development did not proceed uniformly but in a certain rhythm. The rhythm is apparent not only from the curves of the size distribution of particles but also from the curves of the median diameter and sorting. It is also reproduced in the other curves: iron, sulphur, radioactivity, phosphorus, carbon (though more weakly) and porosity (partly). The rhythm is discernible in the stratification; comparatively pure sandstone sections alternate with sections more or less interstratified with argillaceous substances. These substances increase upwards among the interstratified sections, and above the 60-m level (section no. IX) they practically constitute the entire sediment.

The details of the sedimentological development are discussed below in accordance with the division of the sequence of strata employed in the description of the core (chapter IV).

Lower Cambrian

I. 162.15—150 m. The sediment laid down during the initial phase of the submersion will first be discussed.

The grain size is larger than in any other part of the column, but the grains are nevertheless rather small, considering the fact that they constitute the basal layer in a transgression sediment (median diameter 0.88 mm). With regard to roundness, the majority of the quartz particles larger than 250 μ are well rounded; the smaller size grades are somewhat less well-rounded and in part angular ($< 60\,\mu$ chiefly angular). The feldspar grains (mostly microcline), which are of very subordinate frequency, are often unweathered and angular in the larger size grades but most often weathered and rounded in the smaller grades. Grains of tourmaline are well-rounded.

From the discussion on p. 76 f. of the presumable sources of materials it appeared that they are probably derived not only from the granite and allied rocks but also from the quartzite formation in this area. It was also apparent that rounded quartz grains are present in a certain type of granite and in part of the Västervik quartzite formation proper, but the majority of the quartz grains in the parent rocks are angular and the roundness has obviously been brought about, at least for the greater part, after the release of the grains. A long time has been necessary for this procedure of wear and the conclusion may be justified that the transgression was slow in its initial phase (cf. p. 38). The angularity of the feldspar grains was certainly caused by cleavage during the process of wear and is not in contrarity to the fact that the larger quartz grains are well rounded.

Several other facts support the conclusion that the subsidence was slow. The circumstance that feldspar constitutes such a small part of the sediment is one of them. The fairly good sorting of the material is another. The following incidents may also be in accordance with the conclusion that the changes of level were slow, viz. that certain constituents which are frequent in the granitic gneiss have vanished entirely or are very poorly represented in the Cambrian initial sediment. These components are phosphorus, fluorine, iron, and the radioactive substances, which may at least partly be potassium-bearing minerals, such as potassium feldspar. The fact that small quantities of kaolin-like substances occur in the lowermost sample might possibly be interpreted as being contradictory to the above deduction, i.e. that wear and washing were effective and, accordingly, that the water was agitated which also appears from the great angles of bedding. However, the kaolin-like substances were most likely formed secondarily from more or less weathered feldspar. Calcite occurs in weathered parts of the granitic gneiss but the calcite cement in the bottom-most sandstone may be newly formed from calcium-bearing minerals, especially calcareous feldspar.

The further development seems to have continued along the same lines as at the beginning of the sedimentation. The movements in the water were obviously lively to judge from the large maximum angles of bedding, the good sorting of the material (mostly about 1.5—1.6), and the fact that the particles of the larger size grades are well rounded whereas those smaller than 125 μ are mostly angular. The sediment is still rather coarse-grained (for the most part around 300 μ). The feldspar grains have decreased in frequency and are very rare. Rounded tourmaline grains are fairly abundant.

The sediment of this section seems to have accumulated on a beach. Its composition and the roundness and size of the particles are of beach appearance. Further indications supporting this interpretation are the *Scolithus* tubes occurring throughout the section and the slightly salt-tasting clay enclosures.

The changes of level seem to have been still slow. This is indicated by the fact that the general grain size decreased and by the good roundness of the larger particles.

In the upper part of the section certain changes of the sediment appear which seem to foreshadow a different development in the sedimentation. Thin layers of clay substances are interstratified and the curves of iron and radioactivity rise slightly. Chlorite-like substances increase in frequency.

II. 150—134.5 m. The stratification in the "crow rock" of this section is caused by short and irregular clay layers. The "crow rock" is crowded with mainly vertical winding, irregular burrows.

This stratification was obviously caused by repeated interruptions in the movements of the water. There is reason to suggest that these interruptions were due to the tide and that the sedimentation took place on a tidal flat.

The type of stratification in this section is characteristic of tidal flats. The abundance of burrows is also typical of such areas. The thin beds of white quartz sandstone appearing at some levels may be interpreted as gully deposits, particularly as foreset bedding and imbrication of clay cakes can be observed. The rather poor sorting is certainly to some extent due to the fact that each sample comprises both coarse-grained and fine-grained strata.

Recent sandy tidal flat sediments with mud laminations formed at the turns of the tide have often a considerable granulometrical dispersion (cf. e.g. KONING 1950).

The presence throughout the section of clay enclosures (partly salt-bearing) may indicate shallow water. This is definitely manifested by very distinct mud-cracks somewhat below the midheight. The fairly great maximum angles of bedding show that the movements of water were strong as can be expected on a coarse-grained tidal flat. The good roundness of the grains may chiefly have been achieved on beaches in the vicinity.

There are thus many factors which favour the conception that the ancient environment was a tidal flat. This should mean, then, that the site of deposition had changed from having been an exposed beach (section I) to a sheltered area where water entered during rising tide through channels and gullies and from them flooded the flat. The necessary sheltering bars may have been readily created in this subsiding shallow area where sediments were continuously supplied by erosion of weathered rocks and then brought on move.

Before leaving this section the presence of hydrous iron oxide, particularly somewhat above the midheight, will be considered.

Two different suggestions for the occurrence of these reddish-brown striped layers may be put forth. One is that greater quantities of hydrous iron oxide were supplied at intervals. In this case the percentage of iron ought to be high in the red strata, but the iron content, given as iron oxide, in one such layer (140.18 m) was 5.94 % whereas in the greyish-green matrix (140.16 m) it was 6.35 %. The other suggestion is that hydrous iron oxide was intermittently precipitated from water containing bivalent iron. Stagnancy is necessary for storage of bivalent iron, and the precipitation follows immediately when the stagnancy is raised by oxidation which can be brought about for example by storms and by sudden inflows of oxygenated water. In the present case the precipitation possibly occurred according to our second proposition to judge from the fact that the hydrous iron stripes most often accompany somewhat coarser strata in the fine-grained matrix. The changes in configuration necessary for creation of the stagnancy readily may have been achieved by rearrangement of sandy sediments.

Increased supply of hydrous iron oxide was more likely the cause of the appearance of iron stripes in non-fossiliferous sandstones in other parts of the Kalmarsund area. These sandstones were probably deposited in near-shore, ventilated areas where the hydrous iron oxide supplied directly from the weathered Archaean was soon precipitated. As greater quantities of hydrous iron oxide cannot be transported over long distances, neither as gels on account of its hydrophobic nature nor as sols or solutions owing to their very low solubility product at the pH prevailing in the sea, dispersal and contemporaneous precipitation over wide areas are not probable. Correlations of iron-striped sandstones are thus very uncertain, at least over long distances. As appears from our discussion, there are no proofs for correlation of the reddish-brown strata in the present core with the aforementioned red-striped sandstone, so often found as erratic boulders in parts of the Kalmarsund area. (The age of this sandstone was discussed by ASKLUND 1927 who claimed it to be previous to the Cambrian and WESTERGÅRD 1931 who considered it Lower Cambrian in age.)

III. 134.5—124 m. The indications of environment are largely coincident with those which characterize section I. Both may be interpreted as beach deposits. This means that the locality now had reverted to be exposed again after having been sheltered during the formation of section II. This change may easily have been brought about, if, as suggested, the shelter during the previous period was provided by a moving sand bar.

The particles are chiefly of the same size as those which constitute the maxima in the upper part of the previous section and the bulk of the particles in its lower part. Compared with section I the median diameter has decreased to roughly almost the half, but the large-sized fraction 1 mm—500 μ reappeared again after having been practically absent in the upper half of the previous section. The medium-sized fractions (500—60 μ) are abundant, but particles smaller than 60 μ play a comparatively small rôle. Similar general size distribution is often found for recent beach sand (cf. e.g. PETTIJOHN 1949, p. 232 f.). The fact that the majority of the particles larger than 125 μ are well rounded, while the smaller ones are mostly angular is also characteristic of beach sand as well as the circumstance that the sorting is good; it is on the average somewhat better than in zone I (coefficient to a great extent somewhat less than 1.5).

As can be expected for a beach sand, the radioactivity is weak, and the content of iron, carbonaceous substances, and sulphur is low or occasionally none.

The great frequency of *Scolithus* tubes throughout the section (particularly in the lower two thirds) may be another indication of beach environment.

The presence of clay lumps throughout the section as well as a mud-crack in its upper part is in agreement with the other environmental indications.

Certain features in the uppermost part constitute an introduction to the development in the next section: the small-sized fractions increased and the curves of radioactivity, iron, and sulphur rose.

IV. 124—122.6 m. This thin section is similar to section II in structural respect as well as with regard to granulometry, sorting, and roundness of particles. This comparatively coarse sediment is interstratified with clay substances and is crowded with mainly vertical irregular burrows. It may be interpreted as a tidal flat deposit as was the case with section II.

V. 122.6—109.7 m. The lowermost part of this section is a typical exposed shore deposit with fairly coarse, well-rounded quartz particles and nodules of phosphorite at the very bottom. There is no distinct structural discontinuity against the underlying section but it is not entirely excluded that the section boundary IV/V represents a gap. The range of this eventual gap cannot be estimated, however.

The overlying part of the section obviously accumulated under other conditions than the underlying portion of the stratal sequence. This is apparent for several reasons. The grain size changed radically. The median diameter rapidly decreased to roughly one tenth of the values of sections III and IV, viz. from about 100—200 μ to about 10—20 μ. The majority of the particles are smaller than 60 μ, the bulk of them smaller than 20 μ. The fraction 125—60 μ is still rather abundant, but larger particles are as a rule very poorly represented. The sorting deteriorated (coefficient mostly about 2—2.5). Structures also changed in many important respects: long and horizontal or moderately inclined fine-laminations are common, ptygmatized fillings of mud-cracks are abundant in the upper part, and tubes and vertical burrows are absent. Radioactivity increased from the preceding section, and the curves of sulphur, iron, and phosphorus rose considerably.

Many structures, such as swash-marks, dragging trails, and mud-cracks, indicate that the sedimentation took place in very shallow water. The cuneiform elevations on many surfaces can have been formed by the outgoing tide or by the wind. For several reasons mentioned below, the accumulation seems to have occurred in an environment which can be characterized as a mud-flat situated somewhat above normal high tide.

The abundant mud-cracks can scarcely have developed in the few hours which elapse between the diurnal tidal floodings. Longer periods must have been necessary, which is strongly in support of the interpretation that the main part of the section was formed in a somewhat elevated mud-flat area. The filling of the cracks and the covering of the cracked surfaces with relatively coarse, silty sediments may have occurred during the first phase of inflow of particularly high water, such as storm-flows and spring-tides, carrying polymictic suspensions. The subsequent decrease upwards in the size of the particles which is often apparent was certainly due to the fact that the velocity of the inflow successively diminished.

The horizontal or gently dipping parallel stratification in most parts of the section is another support for the suggestion of accumulation on an elevated mud-flat. The irregularities in the stratification which may occur (e.g. scour and fill structures, flow and plunge structures) were certainly caused by the force of the inflow.

Comparatively poor sorting as revealed in this section can be found in recent fine-grained marsh deposits (cf. RUSSELL and RUSSELL 1939, p. 169).

Absence of "worm" tubes, burrows, and sometimes of surface trails favours the conception that the deposit was formed in an area flooded at long intervals. This scantiness of indications of life seems to be contradicted by the high values of sulphur and phosphorus, but these components may be derived from allogene organic debris of various origin which can drift together in environments of the type now considered.

The few fossils present obviously originated from animals which lived in the sea outside the area of deposition. The shells of *Discinella holsti* were found in the shore accumulation in the lower part of the section. The single shell of *Volborthella conica* and the single specimen of the silicious microfossil observed in the mud-flat sediment had certainly drifted in with an influx, judging by their presence in somewhat coarser, silty strata.

The reason for the prominent appearance of calcareous matter and glauconite in this section is not clear.

Calcareous substances were observed in the lowermost part of section I, but they were not discerned thereafter until in the upper part of section III and in section IV where some traces were noticed. In the present section they occur practically throughout, though only with low percentages. Their source is not known. It does not seem very likely that they emanated from calcareous shells. There are nor indications that they were precipitated inorganically or by phytal interaction. They may rather be suggested to be secondary products of calcium-bearing constituents.

It is difficult to know why glauconite became such a conspicuous component here. Only scattered glauconite-like grains were observed at lower levels. Glauconite appears in marine environments only but it can hardly be that such environment was developed here first now; the underlying sections with *Scolithus* tubes and mainly vertical winding burrows were certainly also marine.

The glauconite of this section is probably not an exclusively allogene product formed outside the area of sedimentation. As a great many of the glauconite particles are considerably larger than the largest accompanying quartz grains, they may not be merely a product of enrichment but formed within this area where conditions for their genesis thus may have existed. What these conditions were is not easily known. Necessary sources of material were probably available, such as silica gels, bivalent iron, and potassium; moreover, minerals were present which may be transformed into glauconite such as biotite and possibly illite (cf. p. 41). The fact that the formation of glauconite seems to have been connected with the inflow of water may indicate that the oxygen of this water favoured the glauconitization.

VI. 109.7—90.75 m. In this section the composition of the sediment changed again, and many facts indicate that the deposition occurred to a great extent in an environment different from those of the previous sections.

The white, in part poorly consolidated sandstone between 101.7 m and 92.5 m constitutes the most distinctive part of the section and calls for special attention.

In this sandstone the grain size had increased considerably, the curve of the median diameter running between the limits of about 100 and 300 μ. With regard to the distribution of the particles there is great similarity with section III. The fraction 250—125 μ dominates and 500—250 μ is well represented, whereas the size grades smaller than 60 μ are poorly represented. The sorting is good (coefficient 1.2—1.3) and the larger particles are well rounded. The curves of radioactivity, iron, and sulphur run low, and carbonaceous substances and phosphorus were not observed. Porosity is very high.

This sand was likely deposited on an aggradation flat similar to the Dutch "hooge plaaten" (Plate V, Fig. 5 and Plate VI). These flats are situated somewhat above normal high tide and are flooded at long intervals. Part of them are on such occasions covered with thin clay layers which crack and roll together, and are broken up by wind erosion during the supra-aquatic periods. Thin, partly cracked clay laminations occur at some levels of the present sandstone. Slightly rolled clay flakes certainly from cracked clay strata were also observed. Redeposited clay lumps are abundant. The inundations were obviously too short to enable marine animals to settle, judging by the fact that the sediment is perfectly free from burrows and tracks of animals, which is in accordance with corresponding recent environment.

The sand in such recent aggradation flats forms micro-dunes. The cross-lamination and the great dips which can often be observed in the present sediment may very well have developed in such small dunes. The poor consolidation and the high porosity of our sediment may be the result of considerable removal of the fine particles by wind action.

Recent "hooge plaaten" are rich in shells. In our sediment shells and shell fragments are present, and they are generally worn. Other calcareous substances are practically absent.

Glauconite is scanty in our sediment like in the "hooge plaat" sand on the Dutch Friesian island of Ameland.

The transition from the thin shore deposit at the base of this section is distinguished by intercalations of clay layers and great fluctuations in the median diameter and the sorting which is sometimes very poor. The particles are somewhat less rounded than in the supposed aggradation flat. The abundant and partly ptygmatized mud-cracks indicate the level of sedimentation. Mainly horizontal trails show that the inundations were sometimes of such duration that animals settled there.

Changes in the composition and structures also appeared towards the transition to the overlying section. Greater numbers of clayey strata were deposited, and the median diameter and porosity decreased, whereas the contents of sulphur, phosphorus, and calcareous substances increased. The abundant mud-cracks and mud-cakes show that the deposition took place in the shore zone.

VII. 90.75—84.11 m. The composition and structures changed considerably in this section.

During the first half of this period the sedimentation seems to have taken place in an enclosed area, but the environment may have changed successively first into a mud-flat and then into a sandy back-shore.

The extremely fine and distinct laminations are characteristic features of the section. They are best developed in its lower half. The absence of mud-cracks and mud-cakes in this sediment, where the laminations consist of clay substances in silty parts and silty substances in clayey matrix, may indicate that the area was at that time constantly covered with water. The small grain size, the poor sorting, and the delicate lamination indicate that the site of the deposition was sheltered; the extremely fine laminations may possibly also indicate that the salinity of the water was low (cf. p. 45).

The enclosed area, whether it was a bay with narrow mouth, a lagoon, or a shore-lake, was certainly invaded repeatedly by sea-water loaded with suspensions. The decrease in grain size upwards which can often be observed here in certain strata may be due to gravitational sedimentation from such inflows. Part of them may have been rather violent to judge from the presence of scour and fill structures, plunge marks, and irregularly undulating structures. The numerous *Volborthella* shells at a few silty levels in the lowermost part of the section were probably brought there by inflowing water.

This probably enclosed area seems to have been filled successively with sediments and turned into a mud-flat. This part of the deposit is very similar to the upper part of section V particularly by the presence of ptygmatized fillings of mud-cracks.

In the final phase of this period when a sand layer about 1 m thick and for the most part free from clay substances was deposited the sheltered position apparently had come to an end. This is also indicated by the fact that the curves of radioactivity, iron, and sulphur decrease decidedly; the carbonaceous substances appearing here were certainly enriched secondarily beneath the Middle Cambrian argillaceous shale and accordingly indicate nothing of the environment.

The basal part of the sandstone layer with embedded small clay slabs and with structures showing lively water movements seems to have accumulated in shore position. The overlying parts of the sandstone may have been deposited in the upper shore zone beyond the reach of the tide. The stratification is mostly obscure, but in those parts where it can be discerned the layers are sometimes cross-bedded. This is probably dune-bedding. Such a sediment might possibly also be assumed in certain submarine sites, but in those cases at least some fossils would be expected. The surface of the sandstone is strongly eroded with deep corrosion pits indicating that detraction took place, but its amount cannot be estimated. The absence of the two uppermost stratigraphic zones of the Lower Cambrian, as shown by Mr. WÆRN's investigation of the fauna, can possibly have been the result of such erosion but it may more probably represent a break in the general transgressive movements of the Lower Cambrian sea in the Baltic region (cf. p. 102).

Middle Cambrian

VIII. 84.11—about 60 m. This section, like the following, is different from the Lower Cambrian sections in several respects. Both are fairly monotonous throughout with regard to internal structures and granular composition. The general grain size had diminished considerably. The present section consists of argillaceous shale with intercalating thin strata of light-coloured, somewhat coarser materials. The curve of the median diameter runs for the greater part between the limits of 10 and 20 μ (sometimes it extends to about 40 μ).

The sedimentation seems to have been submarine, but the water was apparently shallow to judge from the presence of dragging trails, and swash-marks in the lower half as well as mud-cracks in the top. The occurrence of flat-rounded fragments of shells may also, according to reasons given earlier in this paper (p. 39), support the suggestion that the water was shallow. The brachiopod shells in the intercalated coarser strata were very likely accumulated because of wave action in shallow water. The occurrence of small quantities of rounded, larger quartz grains (some of them larger than 500 μ but the bulk of them 125—250 μ) may indicate that the distance to the shore was not very great.

The comparatively poor sorting, as well as the very fine, mostly horizontal or only very gently dipping lamination, favour the suggestion that the area of sedimentation was rather enclosed. This condition seems to have been pronounced during the earlier part of this period, when the sorting was particularly poor (below 79 m the coefficient is mostly 2.5—3, max. 3.73), the content of carbonaceous substances fairly considerable, and the lamination especially fine, even and distinct. The fact that the radioactivity and the content of iron are comparatively high and moderately fluctuating is in accordance with these criteria. The content of sulphur is also mostly high, especially in the lower part of the section; aggregates of pyrite appear in greater quantities in this section than in any of the previous ones.

The influence of the tide seems to have diminished compared with the Lower Cambrian. Structures of violent flow and plunge were not observed, and scour and fill structures are rather few. We may conclude that the decrease of the tidal movements was due to certain changes in the coastal configuration. The thickness of this section and its largely uniform development throughout makes it possible that the change was of more than local range. This question will be discussed in the next chapter.

IX. About 60—40.9 m. The environment of deposition does not seem to have changed very much from the previous section. The influence of the tide was probably still small. The rock continuously consists of argillaceous shale. The average median diameter of particles had decreased somewhat (most often about 10—15 μ). The intercalations of mainly silty materials had diminished or disappeared. The lamination had become less distinct; the bedding, when discernible, is mostly horizontal or nearly so, as previously.

Certain temporary changes in the composition of the sediment occurred at the transition to the present section: at the 59 m level the quartz particles are very well rounded like the numerous glauconite grains appearing there and the sorting is much better. The most remarkable change was the sudden strong invasion of trilobites. Since data obtainable from the core are not sufficient to explain these changes they will be considered in a wider connection (cf. chapter VI).

The salinity had possibly increased, to judge from the fact that the fine lamination had disappeared to a great extent; this may not be due to disturbance by animals since their frequency had not increased compared with the previous section.

The area seems to have been shallow as before judging from the presence of flat-rounded shell fragments throughout the section as well as of the mud-cracks, foam-marks, crescent-shaped excavations, and dragging trails in the top. The fact that the pyrite aggregates are worn at various levels, particularly in the top part, also indicates shallow water. In spite of their low frequency the presence of well-rounded quartz grains of larger size grades throughout the section may justify the suggestion that the deposition took place not very far from the shore.

The present sediment, fine-grained and comparatively poorly sorted (coefficient generally above 2, often about 2.5), was certainly laid down under largely similar conditions as in the previous period, i.e. in a fairly sheltered area. However, the ventilation may not have been particularly bad according to the fact that carbonaceous substances are absent or appear in very small quantities and that the frequency of sulphur is moderate. The great increase of sulphur in the uppermost part is obviously due to enrichment of pyrite aggregates in shore and near-shore position.

This top layer seems to have accumulated at the end of a long and slow process of submergence. Thereafter, a long interruption in the sedimentation probably occurred, viz. until the area was invaded by the Ordovician sea.

Basal Ordovician

Only the black Ceratopyge alum shale and the thin transitional layers to the Planilimbata limestone are considered here, as the Ordovician limestone sequence is treated by other authors.

The alum shale obviously accumulated in an area of stagnancy where great quantities of biogene, in part certainly phytogene detritus were deposited. The stagnancy is indicated by the high content of carbonaceous substances, sulphur and radioactive matter. It is indicated indirectly by the fact that the fossils have been decalcified. This must have been due to low pH and that is characteristic of recent stagnant environment. The stinkstone stratum somewhat above the midheight may suggest that the stagnancy diminished temporarily. Large movements of water from the outside may not have occurred since the mineral grains are invariably small. There is no reason to suppose that the alum shale was deposited in deep water far from the shore, but, on the contrary, in an enclosed near-shore area.

The final break of the isolation was successive, as can be deduced from several facts (cf. Fig. 1): the content of carbonaceous substances and sulphur decreased considerably in the uppermost part of the alum shale and the curves descended to very low values in the covering greenish-grey argillaceous layer. The radioactivity decreased to less than half. Also the curves of iron and phosphorus fell. On the other hand, the content of calcareous substances increased. By the growth of the large crystals of calcite which occur in the uppermost part of the alum shale and in the greenish-grey layer the sediment in the latter stratum was squeezed so that original structures were obliterated. Among the quartz particles which are chiefly of the same order of size as in the black shale a few larger grains appeared, possibly indicating increased movements of the water. The comparatively small quantities of glauconite which began to accumulate at that time may be suggested to have developed in connection with the supposed turnover from stagnancy to ventilation.

The overlying bed consisting to more than 50 % of glauconite may mark the definite end of the isolation. Steep current bedding can be observed here and clay lumps eroded from other strata are embedded. These signs of stronger water movements are in accordance with the fact that the median diameter of the quartz grains increased compared with the underlying greenish-grey argillaceous stratum; even particles larger than 500 μ are present.

The glauconite grains are of widely different sizes and shapes. Many of them are several times larger than the largest quartz grains. Most of them are irregularly flat-rounded and part of the surface is often concave. This shape is certainly not due to mechanical wear. This fact and the size distribution of the glauconite grains both *inter se* and in relation to the quartz grains suggest that the glauconite grains were mainly formed in situ. Also the very poor sorting of glauconite-bearing samples from this layer points in this direction. It may be added that phosphoritic nodules appeared at the same time.

After this transitional division the highly calcareous sediments which are characteristic of the remaining part of the Ordovician stratal column began to accumulate.

VI. The Böda Hamn sequence in regional aspect

Detailed comparisons with sequences of strata in other parts of the Baltic region can be made to some extent, but such comparisons are impaired with much uncertainty in many cases. However, information on the general environment of sedimentation can mostly be obtained.

The Lower Cambrian sequence of strata will be considered separate from that of the Middle Cambrian, because they seem to have developed in different environments.

Lower Cambrian

Borgholm. This drilling, about 48 km SSW of Böda Hamn, was brought down in the Lower Cambrian sandstone (WESTERGÅRD 1929). WESTERGÅRD's description indicates that there are apparently similarities with the present stratal sequence but probably also differences.

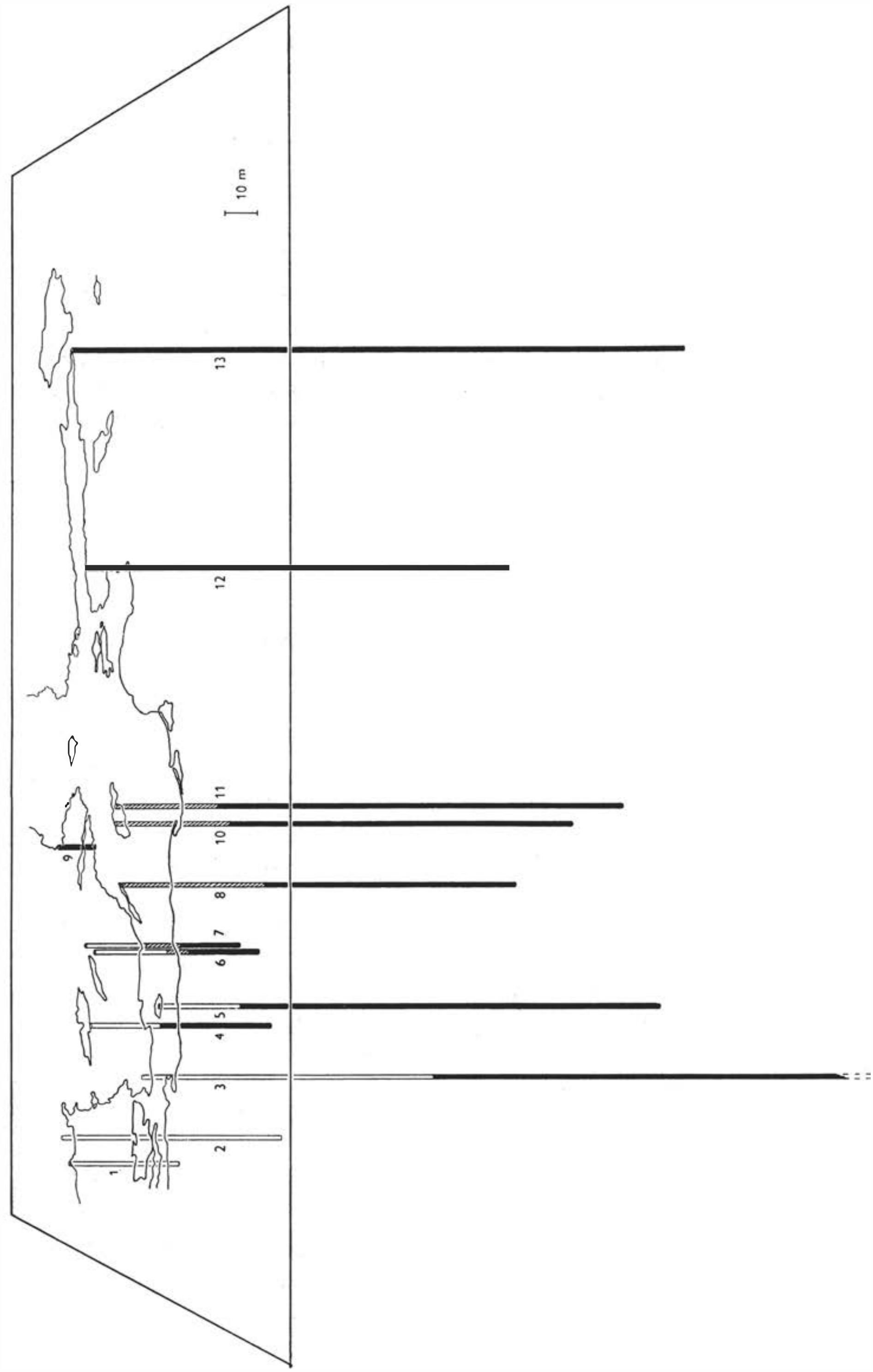
The level of *Discinella holsti* is chosen as starting point in the comparison. In the Böda Hamn core it appears at the base of section V which is certainly an ancient shore deposit. In the Borgholm core it is represented in a portion of about 10 m thickness, most frequently in a conglomerate in the middle of this portion.

A section 4.9 m thick and with the upper limit situated 0.65 m below the said conglomerate is probably a tidal flat sediment possibly equivalent to section IV in the Böda Hamn sequence which is only 1.4 m thick. *Discinella holsti* was not observed in this section but was found throughout that of Borgholm.

The next underlying section in the Borgholm core seems to be a beach deposit which possibly corresponds to section III in the Böda Hamn sequence. These layers are of similar thickness (9 and 10.5 m, resp.).

Proceeding further downwards in the Borgholm sequence we next find a 12.8 m thick layer which chiefly seems to be a tidal flat deposit probably constituting part of a bed that may be paralleled with section II of the Böda Hamn sequence which is about 15 m thick.

In this layer of the Borgholm core is a greenish-grey stratum 1.0 m thick with thin beds and irregular portions of reddish-brown substances,


10 m
1
2
3
4
5
6
7
8
9
10
11
12
13

apparently hydrous iron oxide. Such reddish-brown strata are also present in the Böda Hamn sequence with the upper limit at about the same depth below the upper limit of the supposed tidal flat deposit in which they occur. They were possibly formed as a result of similar environmental conditions in the two localities, probably during a period of comparatively strong stagnation (cf. p. 42). The two localities can have been situated within the same enclosed area, or within different areas developed at about the same time.

Returning to the *Discinella holsti* bearing conglomerate of the Borgholm core in order to compare the overlying parts of the Lower Cambrian, we may notice that glauconite has appeared as a new macroscopical constituent which is also the case in the Böda Hamn sequence, but detailed conformity with regard to environmental conditions during the course of deposition does not seem to have existed.

File Haidar. This locality is situated on the island of Gotland 115 km NE of Böda Hamn (description of the core by THORSLUND and WESTERGÅRD 1938). Our comparison will first comprise the pre-*Discinella* portion.

Correspondence to the supposed tidal flat section IV of the Böda Hamn sequence cannot be recognized, but there is similarity in the lithology in other parts, inasmuch as two sections which may be interpreted as beach deposits are separated by a supposed tidal flat section. These three sections possibly correspond to the Böda Hamn sections I—III.

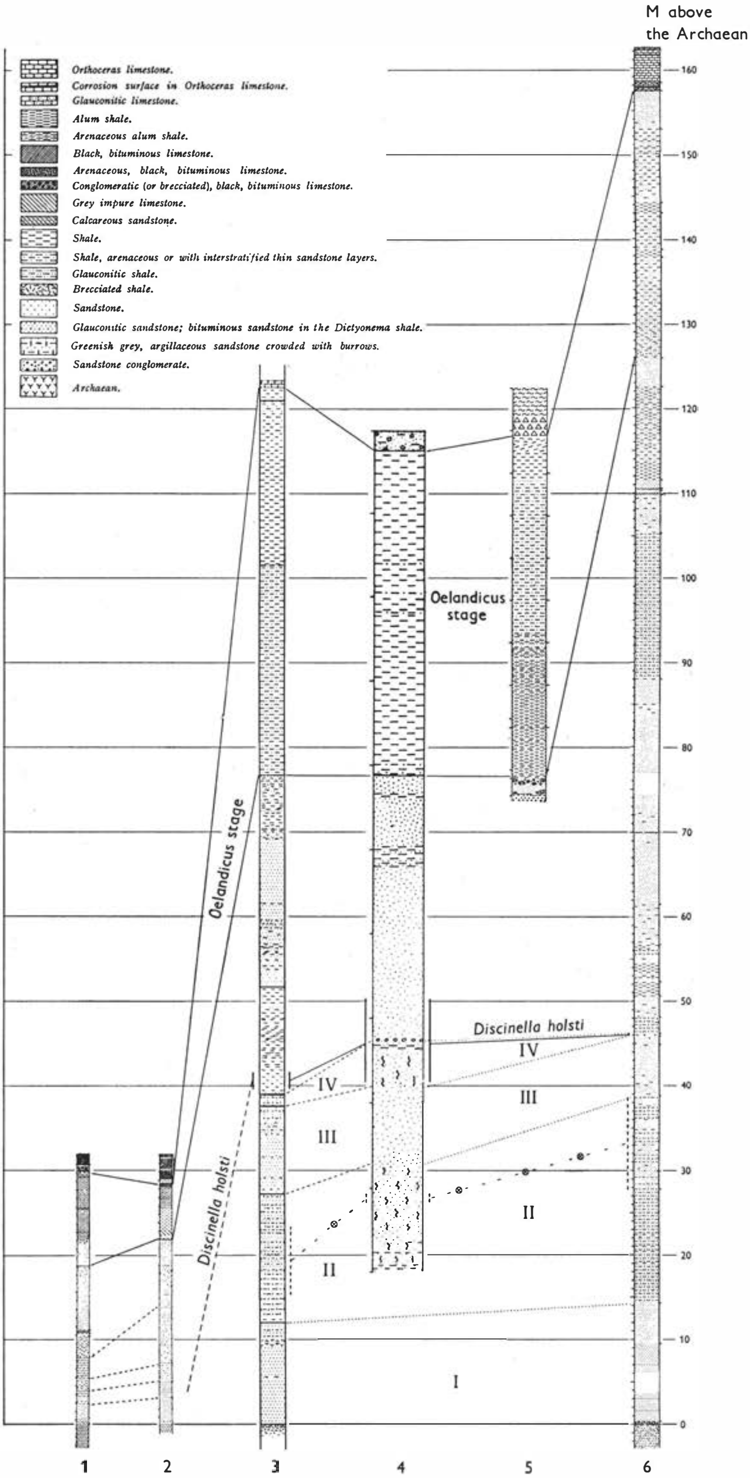
Part of the tidal flat section of File Haidar is impregnated with hydrous iron oxide. The position of this portion largely corresponds to that in the Öland sequences. The precipitation of the hydrous iron oxide may likely have been due to causes similar to those on Öland, thus possibly temporary oxygenation of an enclosed water body. There is, however, obviously no reason to suggest absolute synchronism, but the phenomenon seems to indicate that the conditions for deposition of hydrous iron oxide were favourable at about the same time in different areas of the Baltic region.

Another similarity between the pre-*Discinella* sequences of strata in Öland

Fig. 2. Cambrian cores and outcrops in selection from SE. Norway, S. Sweden, island of Bornholm (Denmark), Estonia, and Ingermanland. (Land contours drawn perspectively from contour map on horizontal leucite plate with hanging bars representing geologic columns.)

Black part of bars: Lower Cambrian; hatched part: the Oelandicus stage; blank part: remaining part of the Cambrian.

1. Rognstrand, Norway, core drilling (verbal communication by Dr. G. HENNINGSMOEN, Oslo). 2. Stablum, Norway, core drilling (reference = 1). 3. Hardeberga, Scania, core drilling, unfinished (EKSTRÖM 1947, p. 16). 4. Kinnekulle, Västergötland, outcrops (JOHANSSON-SUNDIUS-WESTERGÅRD 1943, p. 25 f.). 5. Bornholm, Denmark, outcrops (ANDERSEN 1944, p. 127, 128 and 152). 6. Tornby, Östergötland, core drilling (WESTERGÅRD 1940, p. 6 f.). 7. Bredsätter, Närke, core drilling (ibid. p. 31 f.). 8. The present core. 9. Holmudden at Gävle, South Bothnian area, core drilling (SANDEGREN-ASKLUND-WESTERGÅRD 1939, p. 36). 10. Visby, Gotland, core drilling (THORSLUND and WESTERGÅRD 1938, p. 21). 11. File Haidar, Gotland, core drilling (ibid. p. 11 f.). 12. Tallinn, Estonia, probably percussion boring (ÖPIK 1929, p. 21 f. and RÜGER 1934, p. 8). 13. Leningrad, Ingermanland, probably percussion boring (references = 12 and NEKRASSOFF 1938).


M above
the Archaean
Orthoceras limestone.
Corrosion surface in Orthoceras limestone.
Glauconitic limestone.
Alum shale.
Arenaceous alum shale.
Black, bituminous limestone.
Arenaceous, black, bituminous limestone.
Conglomeratic (or brecciated), black, bituminous limestone.
Grey impure limestone.
Calcareous sandstone.
Shale.
Shale, arenaceous or with interstratified thin sandstone layers.
Glauconitic shale.
Brecciated shale.
Sandstone.
Glauconitic sandstone; bituminous sandstone in the Dictyonema shale.
Greenish grey, argillaceous sandstone crowded with burrows.
Sandstone conglomerate.
Archaean.
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Oelandicus stage
Oelandicus stage
Discinella holsti
Discinella holsti
IV
IV
III
III
II
II
I
1
2
3
4
5
6

and Gotland merits particular attention, viz. the fact that feldspar is very poorly represented and that the quartz grains are largely well rounded, even in the bottom-most part of the cores. This possibly means that the beginning of the Lower Cambrian subsidence was slow also at File Haidar.

The pre-*Discinella* column of File Haidar is about 4—5 m thicker than that of Öland, but the post-*Discinella* sequence is about twice as thick (about 80 m against 38.5 m at Böda Hamn and 30.7 m at Borgholm; in the first case counted from the first appearance of *Discinella*, in the latter from the *Discinella* conglomerate). As in the Öland area, the sedimentation in that of Gotland during the post-*Discinella* division still proceeded under strong influence of the tide, but parallelism to Öland with regard to details in facies does not seem to exist. It may, however, be mentioned that glauconite began to be laid down around the *Discinella holsti* level, thus at the same level where macroscopically discernible quantities appeared in the Öland sequences.

The considerably greater thickness of the post-*Discinella* part of the File Haidar sequence does not seem to be due to the fact that the sedimentation continued in the Gotland area after it had terminated in that of Öland. This is indicated by the fact that *Volborthella* in both areas appears in the top of the Lower Cambrian sequence (at File Haidar about 3—14 m and at Bödahamn about 6 m below the boundary between the Lower and Middle Cambrian). Since, furthermore, the sedimentation in both areas seems to have occurred in the tidal shore zone and definite interruptions in the sedimentation in the considered part of the Böda Hamn sequence cannot be established with certainty but rather in the File Haidar core, viz. at the depth of 389.5 m (cf. Fig. 2 in THORSLUND and WESTERGÅRD 1938) it is very likely that the changes of level during the post-*Discinella* division were more rapid in the Gotland area.

Estonia and Ingermanland. The lithology and stratigraphy are very incompletely known, except for the uppermost parts of the stratal sequence which are accessible in outcrops. Our knowledge of the lower parts is mainly derived from old borings not easily interpreted on the basis of the descriptions.

The thickness increases eastwards from Tallinn to Leningrad, especially that of the upper section (A1 b).

The lower section A1 a (67.9 m at Tallinn and 80.6 m at Leningrad, according to ÖPIK 1929, p. 21) is stated to be composed of coarse sediments with angular grains and with conglomeratic layers at some levels. Clay com-

Fig. 3. Diagrammatic correlation of some lithological features in a number of drill cores in Central Sweden and on the islands of Öland and Gotland. Cf. discussion in the text; geographical positions indicated in Fig. 2; for explanation of symbols in column 3, cf. the folding plate. The columns are reproduced from resp. papers without change except that the scale is unified.

1. Bredsätter (WESTERGÅRD 1940, p. 34 f.). 2. Tornby (ibid. p. 8 f.). 3. Böda Hamn. 4. Borgholm, Öland (WESTERGÅRD 1929, p. 4). 5. Mossberga, Öland (WESTERGÅRD 1936, p. 10 f.). 6. File Haidar (THORSLUND and WESTERGÅRD 1938, p. 11 f.).

ponents occur in comparatively small quantities (ÖPIK, l.c.). RÜGER (1923, p. 123) mentions that, in a boring at Tallinn, the lowermost six metres appeared to be a "Verwitterungsschutt in situ", inter alia rich in red feldspar and hornblende. No fossils were found in A1 a in these early borings. Glauconite is said to be absent and structures do not seem to have been observed.

The Estonian geologist Mr. V. JAANUSSON has informed me that, in the thirties, a number of core drillings were put down in the vicinity of Tallinn and two at Jõhvi in eastern Estonia. The results of the borings at Tallinn have been published by P. KENTS in the Estonian publication Eesti Loodus (Tartu) 1939, and those from the borings at Jõhvi by Prof. LINARI in a periodical issued from the College of Technology of Tallinn; none of these papers are available in Sweden. According to Mr. JAANUSSON, the most important result of the borings at Tallinn was the fact that *Discinella holsti* was not found, though particularly searched for, but that *Platysolenites* was observed practically down to the Archaean. At Jõhvi, where one boring pierced about 500 m of the Archaean it was revealed that a portion of about 8 m thickness in the very top of the Archaean was strongly kaolinized.

Correlations with the cores of Öland and Gotland are very uncertain. One guess might be that the whole Cambrian sequence is referable to the post-*Discinella* portion because *Discinella* does not seem to be present. Another mere guess would be that the A1 a corresponds to their pre-*Discinella* portion because glauconite appears first at the A1b.

From the fact that the kaolinized Archaean is preserved to a great extent and that the basal part of the Lower Cambrian is a "Verwitterungsschutt in situ" we may conclude that the initial subsidence was rapid, thus contrary to what was suggested for the corresponding changes of level in the Öland and Gotland areas.

A lithological change took place with the section A1 b, inasmuch as sandy materials diminished and argillaceous (the well-known "Blue clay") increased; moreover, glauconite appeared. Towards the end of this period the clay substances diminished yielding to sandy materials again: clay and sand occur in about equal amounts in the *Volborthella* zone, but sand is strongly predominant in the overlying *Scenella* zone and, particularly, in the topmost layer, i.e. the so-called Tiskri Sandstone (ÖPIK 1933; also cf. NEKRASSOFF 1938).

Structures below the so-called *Platysolenites* zone which has been the current designation of the uppermost part of the "Blue clay" (cf. the new facts on the vertical distribution of *Platysolenites* cited above) do not seem to be known, but those of the outcropping parts have been thoroughly studied (cf. ÖPIK 1929, p. 42 f. and 1933). These structures indicate influence of the tide as also pointed out by ÖPIK (1929, p. 49). Among them are giant ripples, viz. in the uppermost part of the *Volborthella* zone. The environment was thus of the same general type as in the areas of Öland and Gotland.

Because the underlying parts are insufficiently known the environment of their deposition cannot be determined with a greater amount of accuracy.

Sedimentary rocks of approximately the same thickness had accumulated at Tallinn and File Haidar when the deposition ceased which seems to have occurred at about the same time in the Estonia-Ingermanland area and the Öland and Gotland areas. The Tallinn column is about 1.5 times as thick as the Lower Cambrian sequence of Böda Hamn, and the Leningrad column is about 2.5 times thicker than this one and about 1.7 times thicker than that of File Haidar. Nothing definite is known about the reason for the great thickness of the Leningrad sequence, but it seems likely that the velocity of subsidence was greater.

Bornholm. The lower parts of the Nexö Sandstone are referred to as an arkose and are among Danish geologists generally considered a terrestrial formation. The grain size is not very large, seldom more than 1 mm (HANSEN 1936, p. 173—174). Feldspar grains are present in subordinate quantities compared with the quartz. The particles are often coated with hydrous iron oxide. They are angular in part of the arkose (such as HANSEN's type I which is the basal layer), but in others the angles are rounded (such as HANSEN's types II—IV). HANSEN concludes that the arkose was deposited on the land, possibly to some extent enriched by "Trockenwanderung" (op. cit. p. 115—116). The area of sedimentation was sometimes invaded by the sea; part of the arkose is stated to have been deposited in the zone between low and high water, being thus "eine Litoralbildung im strengsten Sinne" (l.c.).

HANSEN is of the opinion that the initial changes of level were extremely slow. He judges that the supply of materials from the land was so great "dass das Meer nicht imstande war, das zugeführte Material umzulagern und zu entfernen" (l.c.). But if the supplied quantities of materials, even if very large, were not worked and sorted by the sea though being within its reach this may on the contrary indicate that the subsidence was rapid. Time may not have been sufficient to wear and distribute the large amounts of weathering materials according to size. These may chiefly be autochthonous since the arkose layers successively grade into the granite "which is so strongly weathered that it is difficult to judge where the granite finishes and the sandstone begins" (translated from the Danish, ANDERSEN 1944, p. 121).

HANSEN suggests that the overlying so-called Gingham Stone (sandstone striped by hydrous iron oxide) was deposited in an environment intermittently laid bare. This rock is still feldspar-bearing and the grains are often rounded.

The white quartzites which constitute part of the upper section of the Nexö Sandstone consist of well-rounded quartz grains; the quantities of feldspar are small. Glauconite is comparatively abundant. Black quartzites and shales are included in the upper part of this layer. HANSEN considers this alternation as the result of changes between lagoon stages and stages of exposure.

This entire stratal sequence, which was calculated by STEHMANN (1934) to about 35 m but which HANSEN and others estimate at about 70 m, seems to have accumulated in the shore area and under influence of the tide.

HANSEN also published a curve intended to represent the epeirogenetic movements in the Bornholm area during the Lower Cambrian. The curve is rather detailed with regard to the well-known argillaceous and sandy glauconite-bearing green shales situated upon the Nexö Sandstone. The deductions on the changes of the water's depth during this stage which are based, so far as I can see, on the grain size are not quite convincing.

HANSEN's stratigraphical correlations with the Öland and Gotland areas (1937) are obviously uncertain as no fossils have been found in the Bornholm sequence below the middle part of the green shales; only in this section have fossils been found but they are not very elucidative of the stratigraphy.

Scania. The Lower Cambrian stratal column is thick: at Hardeberga where drillings were abandoned without having reached the Archaean it exceeds 125 m (EKSTRÖM 1947, p. 16). In other localities where the contact with the Archaean appears in outcrops it can be observed that the basal layer of the Cambrian is an arkose; in one locality this is about 2 m thick (cf. detailed description of the lithology in HADDING 1929, p. 69 f.). The overlying white Hardeberga sandstone (at Hardeberga more than 94 m thick, according to EKSTRÖM, l.c.) with well-rounded quartz grains and without fossils, tracks, glauconite, and phosphoritic nodules may be considered a shallow water and shore deposit. The presence of large ripples has been interpreted as an indication of tidal influence (TROEDSSON 1927). In the greyish and greenish sandstone overlying the Hardeberga Sandstone proper there are several indications of the influence of the tide. This section can to a great extent be correlated paleontologically with other areas, which is not the case with the white Hardeberga sandstone.

The similarity with Bornholm in lithological respect suggests similar development, inter alia with a rapid subsidence in the initial phase of the transgression to judge from the arkose.

Östergötland and Närke. The Lower Cambrian of these areas seems to be referable to the post-*Discinella* division, as suggested by WESTERGÅRD (1940, p. 23). The thickness is 4—5 times smaller than on Öland and 6—8 times smaller than on Gotland. There is fundamental lithological correspondence with these areas inasmuch as pure sandstone (sometimes with *Scolithus*) alternates with so-called crow rock; the latter constitutes a comparatively greater part than in the Öland and Gotland sequences. These structures very likely indicate that the Lower Cambrian of Närke and Östergötland was developed under the influence of the tide. There is a far-reaching general similarity in the lithological succession among the Östergötland and Närke sequences.

Västergötland. In the classical Lower Cambrian of Västergötland (thin basal arkose, *Mickwitzia* sandstone, and Lingulid sandstone; no "crow rock") there are a lot of structures and marks which indicate that the deposition took place to a great extent on exposed shores, probably under influence of the tide. The inundation seems to have occurred approximately at the same time as in Närke and Östergötland, viz. in the post-*Discinella* division.

Middle Cambrian

From the previous discussion of the genesis of the Böda Hamn sequence it appeared that this area at the beginning of the Middle Cambrian may not have been much influenced by the tide. It was also suggested that this change was of more than local range.

Several areas submerged during the Lower Cambrian were probably land during the Oelandicus stage, viz. Estonia-Ingermanland, Bornholm, and Scania. No deposits in Västergötland can be referred with certainty to the Oelandicus stage (cf. below) and definite proof of the Oelandicus stage in the so-called North Baltic area in the southern part of the Bothnian Bay does not seem to have been produced. The Oelandicus stage is proved in Öland, Gotland, Östergötland, and Närke. For further details, cf. WESTERGÅRD 1946.

The Oelandicus sea thus covered a much smaller area than the largest sea stage of the Lower Cambrian. Communication to the west across Västergötland is not verified and the opening of the Oelandicus sea was probably to the south. We must, however, admit that we know very little about Cambrian sediments in these areas. A boring at Weissuhmen at Königsberg in East Prussia ended in gabbro at a depth of 1364 m, but Paleozoic strata were not pierced; the gabbro is covered by Buntsandstein (information from Prof. SMIT SIBINGA of Amsterdam; the paper by BROCKAMP 1941 describing this boring is not available in Sweden). The deep sub-surface sediments of other parts of the German–Polish region are unknown; the boring at Leba in Pomerania ended in very thick Gotlandian layers (cf. VON BUBNOFF 1941, p. 207). Our discussion of a southern passage from the Oelandicus sea must rely chiefly on the lithology of the Oelandicus stage in Öland and Gotland. The lower part will first be considered, thus, concerning Böda Hamn, the section VIII.

The content of carbonaceous substances is greatest in the lowermost ten metres of this section, the maximum frequency being for the most part about 0.5 %; it is higher in the portion 79.5—78.6 m (1.14 % in a very dark layer at 79 m). The stratification is mainly undisturbed, very fine, and distinct. Section VIII is corresponded stratigraphically in the Mossberga and Borgholm sequences (cf. WESTERGÅRD 1936). There is also similarity in lithological

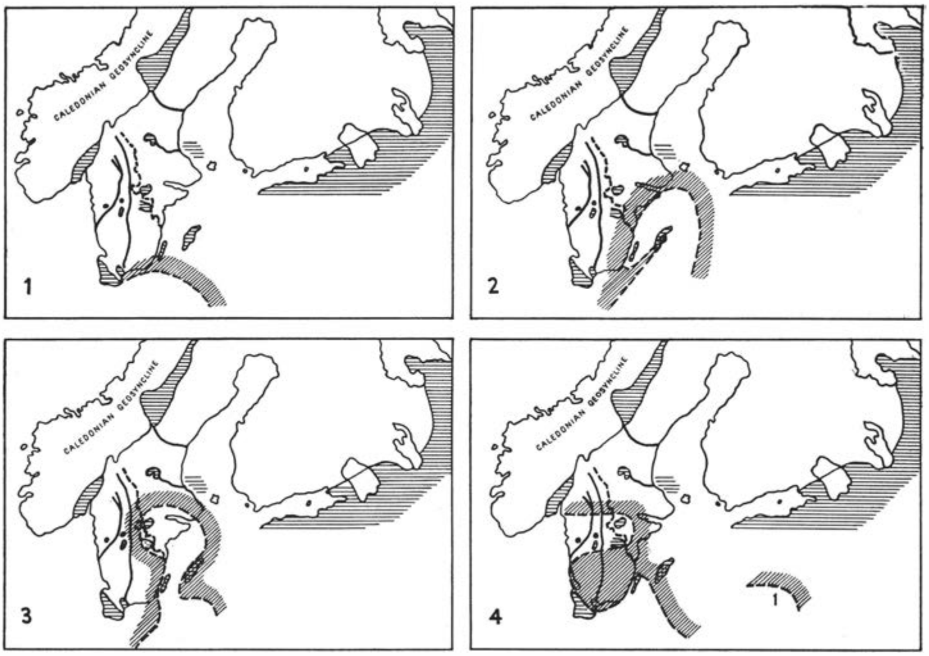


Fig. 4. Possible distribution of land and sea in the Baltic region (minimum distribution of the sea) during the Oelandicus stage (nos. 2 and 3) and the preceding and following stages (1 = *Strenuella linnarsoni* stage; 4 = *Paradoxides paradoxissimus* stage). Hatched areas indicate Post-Archæan in general (from BUBNOFF 1926, Fig. 73). Prominent zones of dislocations in the Archæan (continuous lines) and the eastern boundary of Gothian rocks (dashed line), according to MAGNUSSON–GRANLUND–LUNDQVIST 1949, folding map "Sveriges berggrund". 1. Supposed border of the sea.

respect. The content of carbonaceous substances is possibly even greater than in the Böda Hamn sequence, and the dark shale constitutes a greater part of the section than at Böda Hamn. The difference in this respect is greatest in the Mossberga core where nearly the whole section consists of "a dark-grey or almost black somewhat bituminous clay shale" (WESTERGÅRD 1936, p. 13). At Visby, situated about 20 km SW of File Haidar on Gotland, the Oelandicus stage is mainly developed as greenish-grey arenaceous shale, "but includes, at some levels, rather thick layers of a light fine-grained sandstone. The very top is formed of such a sandstone" (THORSLUND and WESTERGÅRD 1938, p. 21). At File Haidar the Oelandicus stage is mainly developed as sandstone. Greyish arenaceous shales constitute only a minor part. "Very short vertical tubes resembling *Scolithus*" were observed at one level (THORSLUND and WESTERGÅRD 1938, p. 19). According to WESTERGÅRD (1946, p. 15), only the lower portion of the Oelandicus stage, i.e. the *insularis* zone is represented in the Gotland sequence of strata; to judge from another statement of WESTERGÅRD (THORSLUND and WESTERGÅRD 1938, p. 19) the main part of the Oelandicus section of the File Haidar core may possibly correspond to our section VIII. The fauna of the File Haidar core is strikingly scanty both in species and individuals compared with Öland; the specimens are, moreover, poorly preserved.

We have noticed that sand facies is predominant at File Haidar and clay facies on Öland; Visby situated in between is intermediate in this respect. Furthermore, in the Öland cores the clay substances contain carbonaceous matter and the frequency and vertical extension of this matter seem to be greater southwards. The File Haidar area, where *i. a. Scolithus*-like structures were observed at one level, was apparently situated in an exposed position and probably within the reach of the tide. The rapid sedimentary fluctuations there in part of the section considered indicate that the environmental conditions changed repeatedly. These changes may very well have been caused by rearrangement of moving sand masses. The Visby and Öland sequences, on the other hand, may have been deposited in more sheltered areas and we may conclude that they accumulated on the inside of something like a giant bar or Nehrung extending somewhere from the Bornholm area to the vicinity of the area of File Haidar (cf. Fig. 4:2).

The position of the Visby sequence near the mouth of the bay enclosed by this Nehrung seems to be apparent from the fact that comparatively thick layers of sand were deposited on several occasions. Within the Öland section the hydrological conditions were obviously more stable and to judge from the aforementioned statements with regard to the carbonaceous substances the more southern localities may have been situated at greater distance from the outer part of this "Öland bay" bordered to the west by east Småland and to the south and east by the suggested Nehrung.

The sedimentary change at about the 60 m level in the Böda Hamn sequence and the contemporaneous sudden great invasion of the Oelandicus trilobite fauna was probably due to a breaking through somewhere. It would be of interest to locate this place, as far as this can be done on the basis of the present knowledge of fauna and rocks. As a matter of fact, such discussions are always uncertain inter alia because parts of the formations might have been eroded.

There is hardly reason to suggest that the invasion occurred via a passage somewhere between the File Haidar area and the Baltic states. The latter region was apparently not submerged during the Oelandicus stage and, as mentioned above, the File Haidar area also soon seems to have emerged. This passage was thus instead narrowed and probably soon closed. There is, furthermore, no evidence of communication via the South Bothnian area to the Caledonian geosyncline. It is also not very likely that the lithological and sudden faunistical change in the Öland area should be the result of the opening of a passage across middle Sweden. Such a change would have been noticeable within this region itself in a still higher degree than in the remote "Öland bay", particularly as no essential differences in the ecological conditions between the Östergötland-Närke area and that of Öland seem to have existed.

This change did not happen: the fauna is comparatively poor both in Östergötland and Närke. Evidence has not been given that the Oelandicus stage is represented in Västergötland. A glauconite-bearing calcareous layer (maximally about 1 m thick) which occurs in many places in the Skövde and Lidköping areas has sometimes been suggested to belong to the Oelandicus stage but no indicative fossils have been observed (cf. descriptions of official geological quadrangles concerned).

The supposed Nehrung was probably broken through in the vicinity of Öland. The fact that there is no correspondence to the sudden influx of faunal elements in any other part of the Baltic region indicates proximity to the new passage. As the trilobite fauna is more abundant in the Mossberga core than in that of Böda Hamn the assumed new passage seems to have been opened somewhere chiefly south of Mossberga. The following facts may possibly also represent a result of this breaking through in the vicinity. Larger grains, particularly the fraction 125—60 μ, increased considerably at the 60 m level and the level of 59 m is practically the only one in the whole Oelandicus section (except its very basal part) where the fraction 250—125 μ is represented in measurable quantities and where the quartz grains are remarkably well rounded. Great quantities of well-rounded glauconite grains of the same size grade are also present.

The opening of a passage here was possibly directly linked up with more or less local changes of level and configuration during the Oelandicus stage in connection with the gradual tilting towards SW of Baltoscandia during the Cambrian (cf. Fig. 2). We have seen that the passage between Gotland and the Baltic states was very likely narrowed and probably closed. We have also noticed that connection via the South Bothnian area and/or across middle Sweden is doubtful. If thus the outlets of the Baltic basin were strongly reduced or perhaps temporarily closed its level must have risen and the water from the basin had possibly to find new escapes. The assumed Nehrung was in such a case certainly easily forced, especially as the "Öland bay" area was still instable with a largely sinking tendency.

The assumed giant Nehrung may later have been an essential source of material for the chiefly sandy *Paradoxides paradoxissimus* stage. This stage is not represented with certainty in the Böda Hamn core but takes a prominent position somewhat more to the south.

VII. Some concluding remarks

The comparatively moderate changes of level in the Baltic region which have been discussed above constitute only an integrating part of a greater process, viz. an epicontinental inundation which also extended deep into Russia and Poland and thus comprised a great part of the Fennosarmatian platform. This comprehensive depression can be assumed to be a consequence of other changes of level of much greater measure which occurred contemporaneously and/or immediately before outside the margins of the platform.

In the Scandinavian part of the Caledonian geosyncline Eocambrian deposits of great thickness had accumulated, e.g. in the Mjösen district at least about 1 750 m (HOLTEDAHL et al. 1934, p. 319 f.). In the British section of the geosyncline the Cambrian consists of very thick deposits (in N. Wales, for instance, the Lower Cambrian is > 1 200 m, COLE et al. 1917, p. 53) and the Scottish Torridonian sequence which underlies the Cambrian has a maximum thickness of about 6 000 m (op. cit. p. 40). The Cambrian of Bohemia is also thick (the Lower Cambrian 1 100—1 500 m according to VON BUBNOFF 1941, p. 97) and is underlain by pre-Cambrian sedimentary rocks. Such sediments covered by Cambrian strata also occur between Bohemia and Wales. According to CZARNOCKI (1927, p. 18) the Cambrian of the Polish Swiety Krzyz massive situated at the border of the Fennosarmatian shield is of flysch character and has a thickness of 1 500—2 000 m. Continuing eastwards we may note that in the Caucasus massive the Cambrian stratal sequence is thick (maximum of the Lower Cambrian about 800 m according to ROBINSON 1937, p. 17), and turning northwards we find that at the eastern border of the shield (in the so-called Ufa Amphitheatre in the Urals) "the total thickness of the Cambrian is enormous measuring many thousands of metres" (NALIVKIN 1937, p. 8); part of this sequence may be Proterozoic as stated in the same paper (p. 6). North of the shield, in Novaya Zemlya, deposits of the Lower and Middle Cambrian have been found in comparatively recent years (YERMOLAEV 1937, p. 92 f.). These deposits are obviously of great thickness; layers including *Paradoxides* are about 600 m thick.

This heavy load of sediments all around the Fennosarmatian shield certainly contributed to a circum-continental sinking which may also have influenced parts of the continent itself. The Bornholm and the Scanian deposits are situated at the very border of the platform, thus along the so-called TORNQUIST line. There is reason to suppose that the changes of level here have been different from those in the areas situated at greater distance from the margin. It can also be supposed that the downwarping in the beginning was comparatively rapid in the marginal zone. Under such conditions, time can have been too short for thorough wearing and sorting of the materials, so that granulometrically and petrologically polymictic sediments with angular grains were deposited in the initial phase, as was, in fact, also the case both in Bornholm and Scania.

In the Böda Hamn and File Haidar cores, on the other hand, no arkose was developed and the grains in the basal part of the Cambrian are well rounded. The contact against the Archaean is distinct. These facts were assumed to have been caused by slow initial changes of level. At Tallinn, on the contrary, where the Cambrian sequence of strata is stated to begin with an arkose no less than 6 m thick and where the grains in the A1a section are said to be angular, the subsidence may have been rapid. This may also be true for Ingermanland.

As a matter of fact, the Estonia-Ingermanland areas are situated in the continuation of the Carelian zone of the Baltic shield where many dislocations have appeared (cf. VON BUBNOFF 1926, Plate 37 opposite p. 134). The reason for the assumed rapid subsidence might possibly be that this zone of instability easily yielded in the general process of downwarping. The sinking may have terminated relatively soon, and the uppermost part of the Lower Cambrian seems to be missing. This is proved for the entire Middle and Upper Cambrian. These series and part of the Lower Ordovician are absent in Gotland. The uppermost part of the Lower Cambrian, according to WÆRN, 1952, the stage of *Strenuella linnarsoni* and probably also that of *Holmia kjerulfi*, are not developed in the Böda Hamn sequence. These zones have not been observed in Östergötland, Närke, the South Bothnian area, and Västergötland. They were developed in Scania but the *Strenuella* stage has been observed only in the SE. part of this province (WESTERGÅRD 1942, p. 19). The whole inundated region now discussed (with proved exception for Scania) seems to have passed into a supramarine phase. There are no real evidences for a *Strenuella* sea connected to the north with the Scandinavian part of the Caledonian geosyncline, as suggested by HANSEN (1937, p. 174; cf. the map. Fig. 8).

When next time (in the Oelandicus age) the sea invaded parts of these areas we may consider this as the birth or possibly the Paleozoic renaissance of the Baltic Sea. To the east there was certainly a coast line somewhere between Gotland and the Baltic states. To the west the coast line seems to have been essentially identical with that which was developed in the Lower Cambrian *Mickwitzia monilifera* age. It may thus have extended approximately along the modern coastal zone of Småland and then along the border between the Gothian Småland granite and porphyry rocks and the Sveco-Fennian thrust region of the eastern half of Central Sweden. In Närke obviously a passage had existed across middle Sweden in the *Mickwitzia* age but later this passage seems to have been closed by the threshold area of the Kilsbergen mountains situated just east of the important fault line between the Gothian and the Sveco-Fennian rocks.

Whether the border to the north was about the same as during the *Mickwitzia* age is not established; as mentioned in the preceding chapter it is not verified whether the Oelandicus stage of the Baltic basin extended to the South Bothnian area at all which was the case during the *Mickwitzia* age. The previous discussion also lead to the conclusion that the Baltic Sea in the first phase of the Oelandicus age was not wide open towards the south but that the passage was situated somewhere between Gotland and the Baltic states. The Öland area may thus have been situated in a large bay enclosed in SE by a Nehrung (see Fig. 4:2).

The submergence of the Östergötland—Närke area probably followed after that of the Öland—Gotland areas (to judge inter alia from statements given by WESTERGÅRD 1946, p. 15 and 17). In this way the development during the transgression of the Lower Cambrian was repeated. Comparing, on the other hand, the area of Östergötland—Närke with the South Bothnian area, the latter was inundated earlier in the Lower Cambrian, to judge from the fact that *Discinella holsti* is reported from the South Bothnian area but not from Östergötland—Närke. Whether this order of events was repeated in the Middle Cambrian is not verified since, as mentioned, no proof of the Oelandicus stage in the South Bothnian area has been found.

During the following development in the Middle Cambrian essentially the same changes of level took place as during the later part of the Lower Cambrian so far as the obviously very shallow Baltic depression was laid bare in the *paradoxissimus* age except for the most southern parts. The Östergötland—Närke area was still inundated but at that time connected with Västergötland.

When, later, the great Ordovician transgression occurred the ancient Oelandicus sea re-filled, also the South Bothnian area, from where the sea expanded even farther over Gästrikland into the Siljan district. Parts of the middle Swedish region were inundated again, but the Gotland area does not seem to have submerged. On the other hand, the Estonia-Ingermanland area was depressed which favours the aforementioned suggestion, viz. that it was comparatively unstable and readily yielded to the geophysical forces which ruled the general changes of level in the Baltoscandian section of the Fennosarmatian platform in the early Paleozoic.

The above-mentioned deductions are incomplete and uncertain possibly also with regard to certain major features. The existing deposits are still insufficiently known and the extent of erosion is difficult to establish. They indicate at least that the Cambrian changes of level were complicated in the Baltic region and that certain general features can be discerned, indicating, for instance, that the changes of level seem to have been governed to some extent by pre-existing geological structures.

Summary

The Cambrian and basal Ordovician portions of a drill core from Böda Hamn in the northern part of the island of Öland in the Baltic Sea constitute the object of this investigation.

The main purpose was to reconstruct the local environment of deposition on the basis of sedimentological and also faunistic data (as for the fossils, cf. WÆRN, 1952). This involved a study of the continuous development of the relation between the level of deposition and the level of the sea, that is the ancient changes of level. The sediment was examined as comprehensively as possible in order to obtain a broad base for the reconstruction of the environment (cf. folding plate).

Three periods of transgressive movements can be distinguished: one comprising the Lower Cambrian except its latest parts, the second the Middle Cambrian except its later part, and the third the Ordovician.

The following main types of environment during the Lower Cambrian transgression were interpreted to have succeeded each other:

I. Tidal beach
II. " flat
III. " beach
IV. " flat
V. Mud-flat situated somewhat above normal high tide, grading into:
VI. Supramarine aggradation flat, occasionally flooded
VII. Bay with narrow mouth or shore lake, passing into mud-flat and finally supramarine backshore.

A certain amount of environmental parallelism with other parts of Öland and possibly Gotland can be traced for the pre-*Discinella* division. The environment in the Östergötland-Närke area was of similar type. These areas may have submerged slowly but those of Scania, Bornholm, and Estonia-Ingermanland more rapidly.

The history of the Oelandicus stage of the Baltic region merits particular interest.

The latest part of the Lower Cambrian appears to have been a period of general regression in the Baltic region, and except for the most southern parts, the whole region may have been land at that time (Fig. 4: 1). The following Middle Cambrian transgression resulted in the submergence of only a small portion of the region, including the Öland area. The water was apparently shallow there. The influence of the tide in this area seems to have diminished considerably compared to the Lower Cambrian. This may be due to certain topographical changes of wide extent.

The present core and other cores from Öland and other parts of the

Baltic region seem to indicate that the Öland area was situated in a large and wide bay closed to the south during the first division of the Oelandicus stage (section VIII). This bay may have been bordered to the south and east by a long sand bar extending from the Bornholm area to somewhere about N. Gotland where the outlet of this early Oelandicus sea stage may have been situated (Fig. 4: 2).

During the Oelandicus stage this outlet and its continuation southwards outside the supposed bar seem to have been narrowed and possibly closed. The water level in the Baltic basin may have risen with result that the above-mentioned Nehrung may have been broken through somewhere south of Öland. This is indicated particularly by the sudden invasion of an abundant trilobite fauna in the very beginning of section IX (Fig. 4: 3). This invasion had no correspondence in other parts of the Baltic basin. Section IX is lithologically different from section VIII in lacking the arenaceous laminations so characteristic of the latter.

The changes of level and topography as now touched upon constitute details of the major changes of level which was a tilting towards SW of the whole Baltoscandian region (cf. Fig. 2). After the Oelandicus stage the sea seems to have receded from the greater part of the Baltic basin, the northern shore probably having been situated at the latitude of N. Öland (Fig. 4: 4).

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Explanation of plates

Plate I

Fig. 1. Lobate plunge structures. a. Plunge grooves. b. Sand fillings. Nat. size. 121.4 m.

Fig. 2. Ptygmatized and pushed fillings of mud-cracks. Nat. size. a: 111.81—111.69 m. b: 111.95—111.90 m (both split surfaces). c: 112.15—112.12 m (polished surface).

Figs. 3—6. Vertical tubes and burrows. Figs. 3—5 slightly retouched. Figs. 3 and 4: *Scolithus* tubes penetrating clay strata, in fig. 4 partly ramifying. Fig. 5. Vertical tubes ramifying in a clayey layer. Fig. 6. Winding burrow in reddish-brown stratum. Nat. size.
Fig. 3: 133.86—133.81 m (outer surface of core).
Fig. 4: 132.18—132.12 m (split surface). Fig. 5: 152.56—152.51 m (split surface). Fig. 6: 141.19—141.12 m (split surface).

Plate II

Fig. 1. Swash marks on modern shore. Woods Hole, Massachusetts.

Fig. 2. a. Tiny ridges from the level 76.82 m interpreted as swash marks. Nat. size.
b. Ridge of the type shown in Fig. 2 a from the core in transverse section. 80 ×.

Fig. 3. Counterparts of core from the Lower Cambrian sandstone (142.18—142.15 m). a. Natural state. b. Heated. Cf. the text, p. 51. Nat. size.

Fig. 4. Core section II ("crow rock"). Median longitudinal split surface. 146.0—145.87 m. Nat. size.

Plate III

Fig. 1. Core section V. Mud flat, silty part. Median longitudinal split surface. Nat. size. 115.72—115.56 m. Glauconite lamination in the upper part, in the lower portion both greenish-grey clay lamination (fine, dark laminae) and glauconite lamination.

Figs. 2 and 3. Core section VII. Sedimentation in enclosed water body. Fig. 2. Structures developed during inflow. Fig. 3. Mainly undisturbed sedimentation. Median longitudinal cuts. Nat. size.
Fig. 2: 88.65—88.56 m (polished surface). Fig. 3: 88.06—87.98 m (split surface).

Plate IV

Figs. 1 and 2. Core section VII. Alternating regular lamination and irregular structures developed during inflow into enclosed environment. Median longitudinal cuts. Polished surfaces. Nat. size.
Fig. 1: 85.95—85.92 m. Fig. 2: 88.13—88.08 m.

Fig. 3. Conglomerate at the transition from the Lower Cambrian (a) to the Middle Cambrian; b = glauconite layer, c = basal part of the dark lower portion of the Oelandicus shale. Split surface. Nat. size. Note the deeply corroded upper surface of the bituminous Lower Cambrian sandstone. The large pebble in the conglomerate is obviously derived from this sandstone layer. Most of the smaller pebbles are phosphoritic nodules.

Fig. 4. Conglomerate at the transition from the Middle Cambrian to the Ordovician. Polished surface. Nat. size.

Plate V

Figs. 1—4. Core section VIII (Oelandicus shale). Median longitudinal split cuts. Nat. size.
Fig. 1: 82.98—82.93 m. Fig. 2: 76.21—76.16 m.
Fig. 3: 79.19—79.15 m. Fig. 4: 63.95—63.89 m.

Fig. 5. Aggradation flat with small barchan dunes in the northern part of the Dutch East Friesian island of Ameland. Cracked and rolled thin clay layers on the sand surface between the dunes.

Plate VI

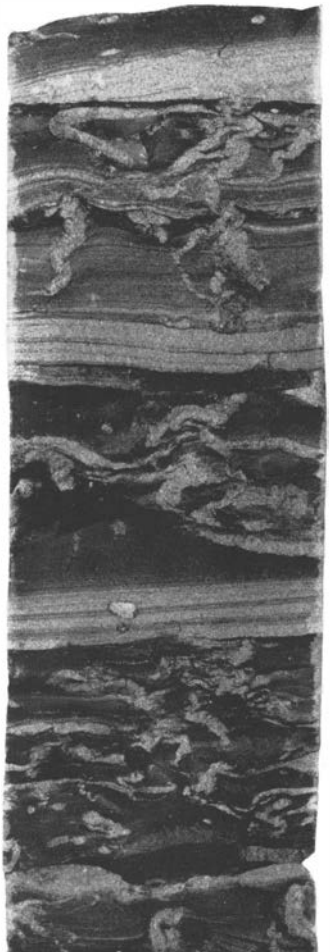
Air view from the northern part of the Dutch East Friesian island of Schiermonnikoog, showing to the right aggradation flat flooded only during exceptionally high (storm) tides. The surface is covered with small dunes arranged rhythmically. To the left large dunes. In the upper part the North Sea with beach and bars, in the lower part a portion of the tidal flat. Distance from beach to tidal flat nearly 2 km.

Folding plate

Comments on the lithological data represented in the plate are given in the text.
The distribution of the macrofossils was examined by Mr. WÆRN, who also described the microfossils released in the disaggregation of the sediment for granulometrical purpose. A full account of the fauna is given in his paper, 1952.

1a

1b



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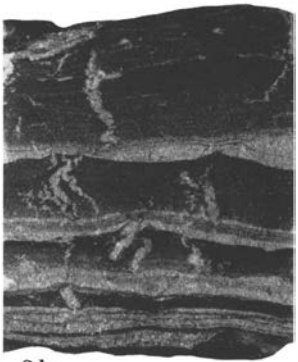

2b

2c

3

4

5

6

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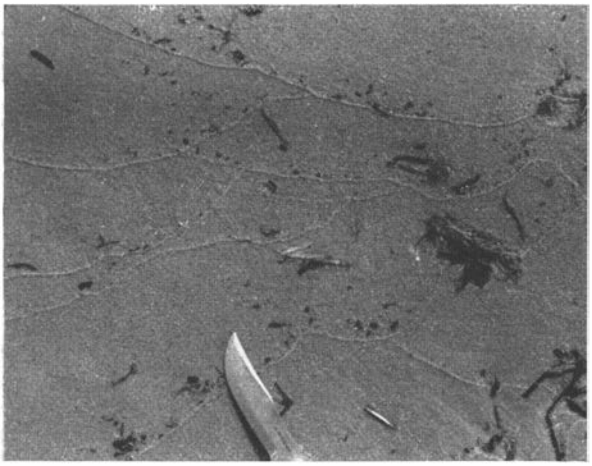

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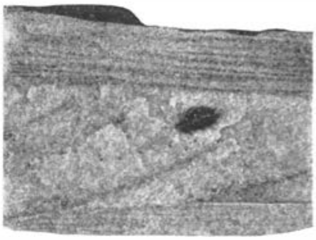

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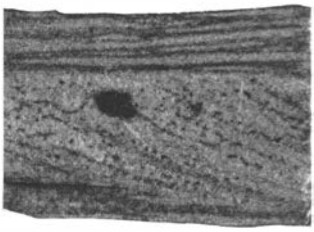

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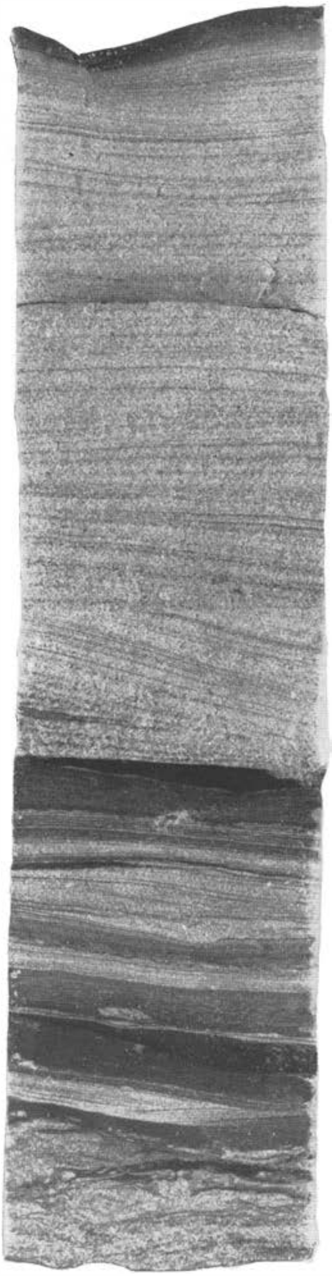
4


2b

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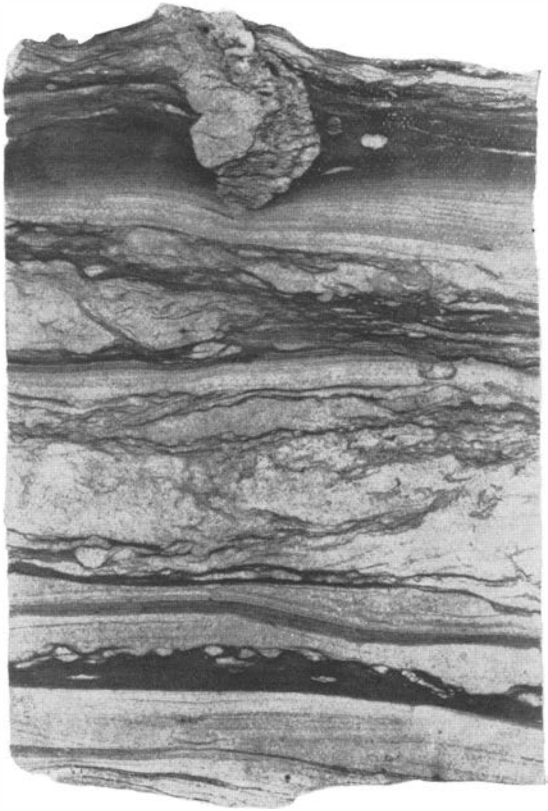

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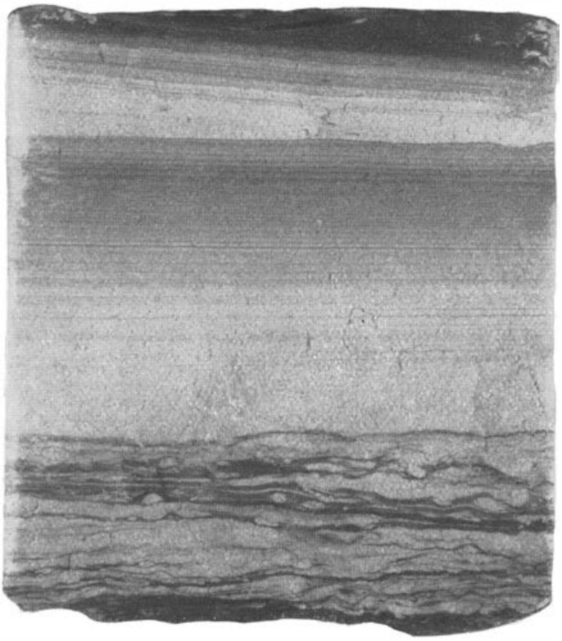

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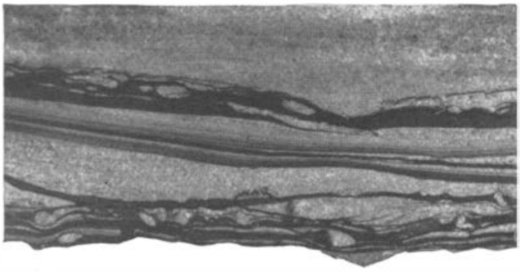

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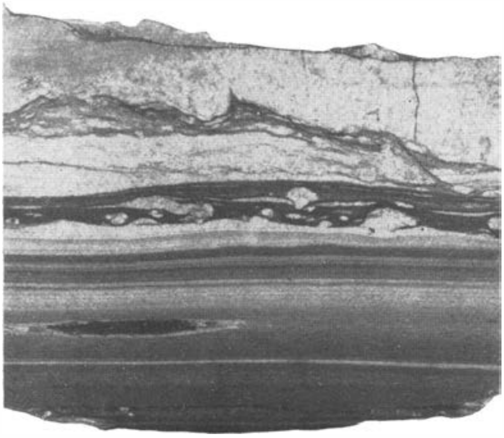

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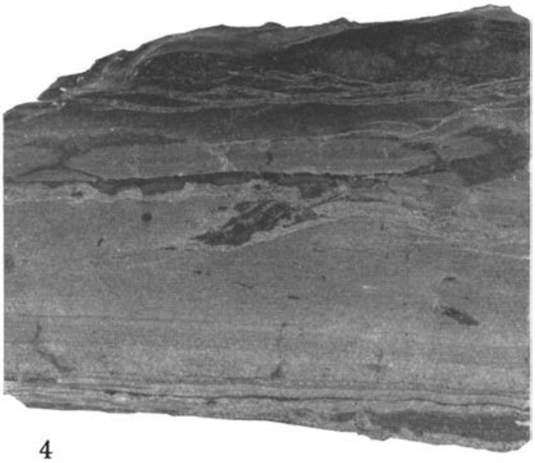

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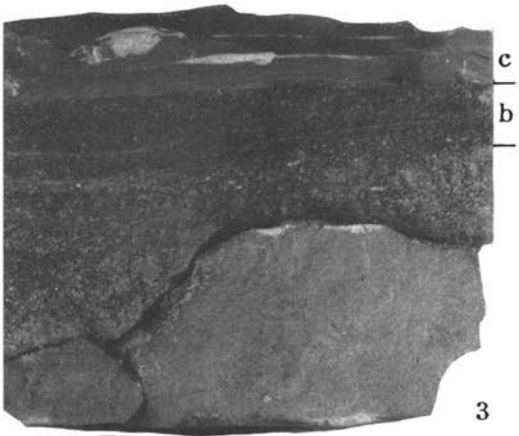

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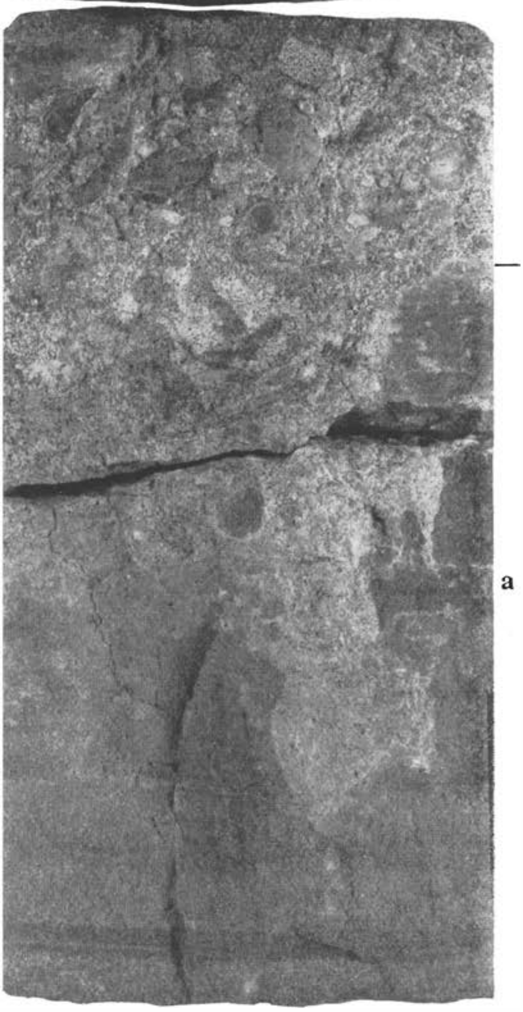

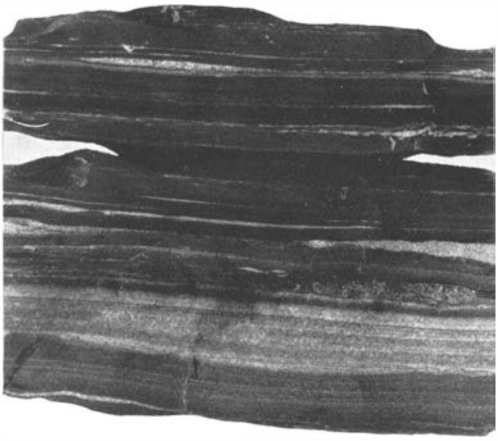
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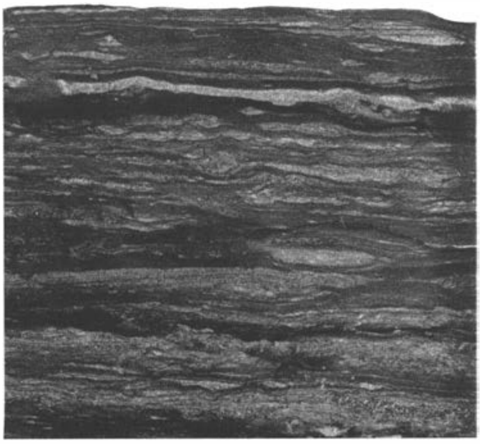
3


4


5

M below rock surface
Calcareous substances
Glauconite (- laminations, · single grains)
Greyish-green clay laminations
Arenaceous laminations
Hydrous iron oxide
Bituminous substances with graphitoid matter (•), bituminous iron-bearing nodules (•)
Enclosures of kaolin (∘) and greyish-green clay substances (•, S=salt-bearing)
Phosphoritic nodules
Pyrite
Feldspar crystals (∘), garnet (•), tourmaline (•), galena (•)
Ptygmatized fillings of mud-cracks
Mud-cracks (•), swash marks (→), foam marks (→), crescent-shaped shore marks (∘), dragging trails (—)
Trails and tracks (straight —, irregular ~), ripple structures (~)
Flat-rounded fragments of fossils
Roundness of quartz grains (majority rounded majority angular)
Explanation of symbols in the head column
Limestone
Alum shale
Sandstone
Archaean
Argillaceous shale
Argillaceous shale with laminations of coarser materials
Very thin argillaceous laminations
Coarse and irregular argillaceous laminations
Mainly vertical, irregular burrows
Size distribution of particles
Maximum angles of bedding
Symbols, cf. →
> 2 mm
2 – 1 mm
1 mm – 500 μ
500 – 250 μ
250 – 125 μ
125 – 60 μ
60 – 20 μ
< 20 μ
Median diameter of particles
Sorting of particles
Porosity
Radioactivity
"Total iron" (—) given as iron oxide (—) + pyritic iron
Sulphur
Carbonaceous substances
Phosphoric anhydride
Carbonate substances (chiefly calcium carbonate)
Ordovician
Middle Cambrian
Lower Cambrian
IX
VIII
VII
VI
V
IV
III
II
I
Bröggeria salteri
Acrotreta spp.
Obolus apollinis
Paradoxides paradoxissimus?
Peronopsis fallax
Condylopyge regia (•)
Ptychagnostus praecurrens (∘)
Hyolithes sp.
Paradoxides sjögreni (•) and P. insularis (∘)
Paradoxides of the oelandicus group
Ellipsocephalus polytomus
Undetermined brachiopods
Acrothele granulata (mostly fragments below 60 m)
Acrotreta spp. (•)
Lingulella ferruginea (∘)
Silicious microfossil
Volborthella tenuis
Torellella laevigata
Volborthella conica
Discinella holsti
Scolithus linearis
Scolithus linearis