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THE PRE-QUATERNARY SEDIMENTARY ROCKS OF SWEDEN

BY

ASSAR HADDING

VII.

CAMBRIAN AND ORDOVICIAN LIMESTONES

WITH 193 FIGURES IN TEXT

LUND
C.W.K. GLEERUP

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Read before the Royal Physiographic Society, April 10, 1957.

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CONTENTS.

Preface.

When the author in 1941 published an investigation into Reef Limestones, the sixth part of the present series on The Pre-Quaternary Sedimentary Rocks of Sweden, he hoped shortly to be able to complete the seventh part, which was to embrace the stratified limestones. However, for a period of several years his time was claimed almost exclusively by administrative and other practical duties. When work on the book could be resumed in earnest, it became clear that the subject-matter was so great that only a limited selection could be dealt with. Economies in space and expense were achieved by means of a simplified, schematic account and reference to the illustrations. Even so, for economical and practical reasons publication had to be in two parts. The first part, now to hand, comprises a review of the general character of the stratified limestones and an examination and illustration of selected Cambrian and Ordovician limestones. The second part is to contain an account of Silurian and Mesozoic limestones and a summary of the views and conclusions which may result from the investigation. It will also contain a table of the numerous chemical analyses. The author hopes to deal with certain special problems separately.

A systematic division of the calcareous sediments may be based on their characteristics, e. g. their texture and structure, their content of detritus, or different limestone-forming organisms. The varying characteristics of limestones generally reflect their mode and environment of formation. These should, if they can be established, form a good basis for a broad systematic division of limestones. The details of the system are of a more varying character.

In the account now published the author has considered it inappropriate to anticipate the attempt to find a good systematic lithological division of the subject-matter. That must be deferred until the final chapter of the following part. Instead, the author has described the rocks in the stratigraphic order in which they were formed.

As the nomenclature should, if possible, be linked naturally to the system, the author has been unwilling to commit himself in advance and employ throughout certain generic terms, e. g. calcilutite and calcarenite. On the other hand, generally descriptive terms have been widely used. In several cases, perhaps in most, others might equally well have been chosen. Fragment limestone, microcoquina limestone, arenaceous or glauconitic limestone are frequently used terms. They can hardly be misunderstood, yet there are rocks to which all of them could apply. This is true of other terms, too. In most cases the limestones have only been named according to the zone, stage, etc. in which they occur. The stratigraphic division is not, however, uniform, and as it has been beyond the author's task to discuss or correct it, the stratigraphic terms are somewhat variable. Accompanying tables and sections should, however, clearly show to what the terms refer.

Certain sections of the work have been pursued over a period of fifteen years. They have been partly revised, but there are still shortcomings. They are not, however, of a kind to impede further research. The author would have liked to have time to rewrite the book, but it would have been at the risk of neglecting other, more important tasks. When a man is well beyond his retiring age, he knows that his time is short.

The material on which the investigation has been based is the property of the Mineralogical-Geological Institute of Lund University. The bulk of it has been collected by the author. The thin sections were made by Hugo Wihlborg. The translation into English was carried out by Peter Green M. A.

A grant in aid of printing was made by the National Scientific Research Council.

GENERAL LITHOLOGICAL CHARACTER OF STRATIFIED LIMESTONES.

Composition of limestones.

Limestones are chiefly composed of calcium carbonate, but they also contain as a rule other constituents and sometimes in such quantity that they characterize the rock. Argillaceous matter and sand are common admixtures, and when they appear in large quantity the limestone merges into marl and marly clay or arenaceous limestone and calcareous sandstone, respectively. Other admixtures in limestones are less important quantitatively but often very prominent in the colour of the rock, its chemical character or physical properties. Bitumen, iron sulphide, oxide, and hydroxide, glauconite, phosphorite, and silica are substances of this type which are common in limestones.

The nature of the constituents, their development and occurrence are indicative of the conditions and environment of formation of limestones. In the following report these factors will be discussed and exemplified.

The organic element in limestones, i. e. the calcium carbonate formed with the assistance of organisms, is generally predominant. The author has earlier presented a general survey of the importance of the various plant and animal groups as limestone-formers (Hadding 1933) and will therefore refrain from going further into the question here. The following account will instead deal with various types of limestones marked by the development and appearance of their fossil material. Particular attention will be paid to the accumulation and secondary occurrence of the material together with its crushing, corrosion, and recrystallization.

The constituents of limestones are dealt with in the following order:

A. Carbonates

- I. Calcite
  - a) Calcite aggregates
  - b) Calcareous fossils as rock-formers
    - 1) Authigenic macrofossils
    - 2) Macrofossils and fragments resedimented secondarily

3) Microfossils and microfragments
4) Calcareous mud precipitated with the aid of organisms

c) Inorganically formed, chemically precipitated calcite (and oolites)

II. Aragonite
III. Dolomite

B. Other rock-forming materials

I. Argillaceous matter
II. Silica
III. Glauconite
IV. Phosphorite

C. Impregnations and diagenetically and metasomatically formed inclusions

I. Pyrite. Marcasite
II. Limonite. Siderite
III. Barytes. Strontianite
IV. Cordierite

Carbonates.

Calcite.

Aggregates and crystals of calcite.

Limestones are chiefly composed of calcite aggregates with anhedral crystals. They are largely diagenetically recrystallized fossil fragments. Only in special cases are the fragments single crystals (pelmatozoans); in general they have been transformed to granular or fibrous aggregates (molluscs, trilobites, etc.) and in certain cases to micro- or crypto-crystalline aggregates (calcareous algae).

The calcite crystals of the aggregates may be of varying size. In dense limestones, e. g. lithographic limestones, the grains may be less than 0.005 mm, in macroscopically fine-crystalline limestones more than 0.1 mm in diameter (figs. 1 and 2). Larger calcite crystals, more than 2 mm, are found in coarse fragment limestones, in bituminous limestones (anthraconites), and in limestones which have been subject to more or less clear regional or contact metamorphism.

Radiated calcite often occurs as a crust on fossil fragments (fig. 3). Occasionally the radiated crust remains after the fossil has been completely dissolved. Columnar calcite is often found in anthraconites, generally radiating from a core: a limestone pebble or a fossil fragment.

In part freely developed are the calcite crystals which are found in cavities or cracks in limestones. They display various shapes: prismatic and tabular or obtuse and acute rhombohedra and scalenohedra. They are of no importance for the sedimentation problems dealt with here, and their formation will not, therefore, be

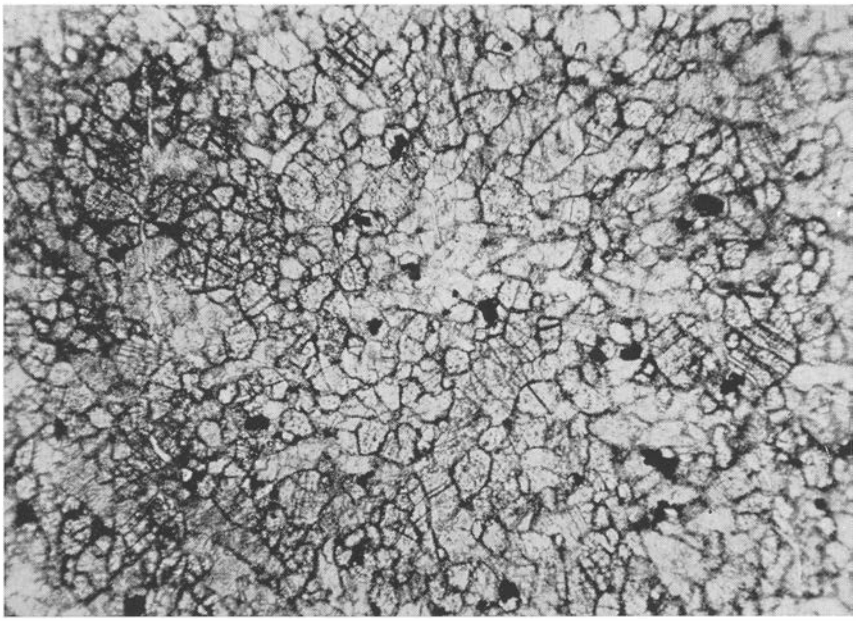

Fig. 1. Microcrystalline limestone, macroscopically dense. Planilimbata limestone. Ottenby, Öland. (Prep. 3007 b, photo. 1322.) — 60×.

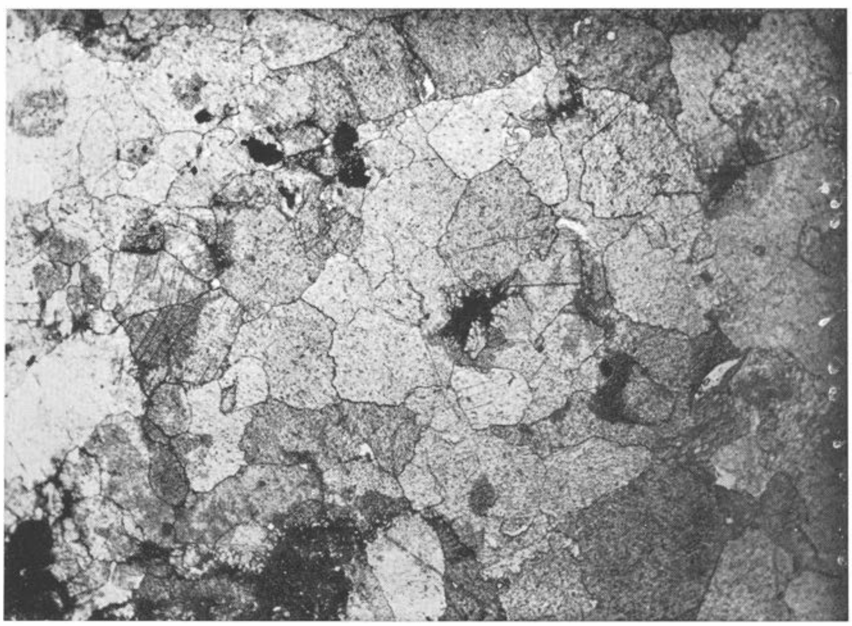

Fig. 2. Crystalline limestone. Ceratopyge limestone. Mossebo, Hunneberg, Västergötland. (Prep. 8820 b, photo 1605.) — 20×.

Fig. 3. Calcite crust on fossil fragments. Tretaspis limestone. Amtjärn. Dalarna. (Prep. 7213, photo 1653.) — 20 ×.

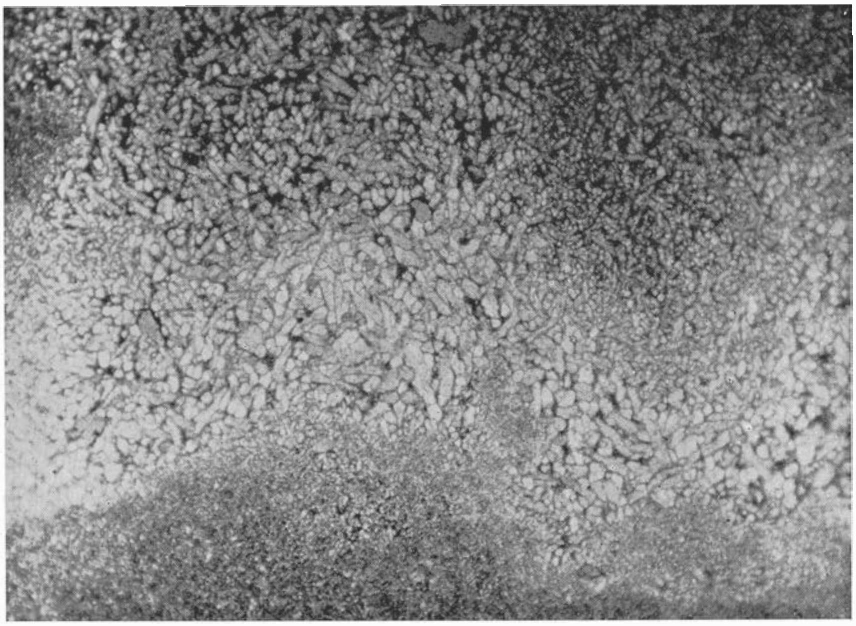

Fig. 4. Calcite grains in limonitic matrix. Planilimbata limestone. Skattungbyn, Dalarna. (Prep. 7825, photo 1689.) — 20 ×.

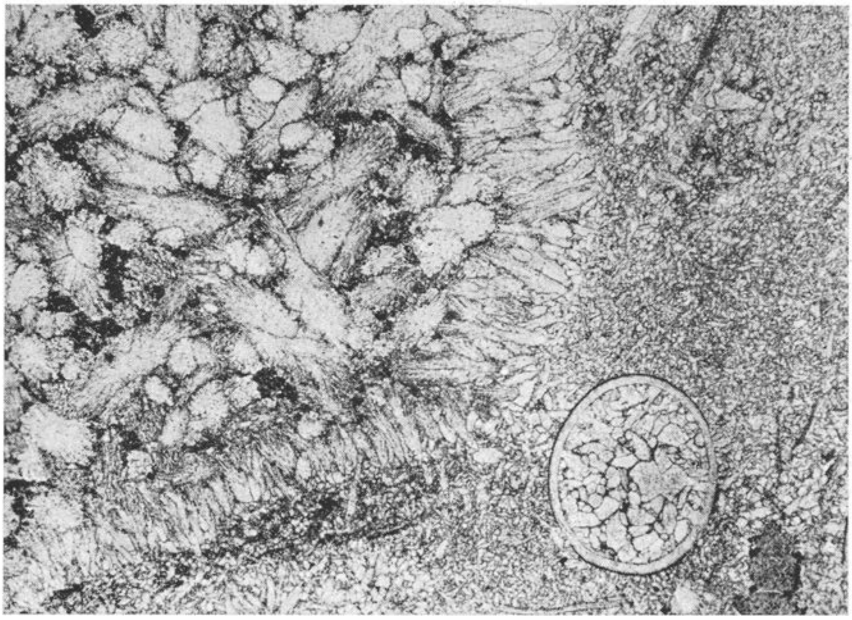

Fig. 5. Calcite crystals of different shape and size. Middle Cambrian anthraconite. Västergötland. (Prep. 6931, photo 1353.) — 20×.

discussed. Relatively freely developed and of greater interest are the calcite crystals which occur "in suspension" in a matrix. These often have the shape of grains of wheat (fig. 4), more seldom of blunt rhombohedra. The "suspended" and the radiated crystals of the anthraconites may be frayed or ragged in the peripheral zone or throughout (fig. 5).

Limestones composed of calcareous fossils.

Limestones with authigenic macrofossils.

A limestone may be principally built up by calcareous organisms. Recent and fossil reef limestones are examples of this. The author has already (1941) dealt with this group of limestones and will restrict himself here to recalling that various types of these rocks occur in the Swedish series of strata: the Ordovician-Silurian algal limestones of Dalarna, the Upper Silurian stromatoporoid-coral-algal limestones of Gotland, and the coral limestones of the Danian of Skåne. The reef limestones are not only composed of reef-building organisms, which may be of different kinds in one and the same reef, but also to a large extent of other materials. These consist mainly of benthogenic calcareous organisms and of more or less crumbled fragments of both the latter and the reef-builders. The benthogenic elements in these rocks must be considered as occurring authigenically, even if they are fragmentary and clearly corroded. The organisms which are represented in the materials have all lived on the reefs, and they belong, therefore, to the same environment as the remainder of the rock.

The same views as have been put forward above concerning the benthogenic elements of the reef limestones can also be applied to the macrofossils in many of the stratified limestones. The fossils found in limestone beds which do not show any signs of secondary resedimentation most probably occur authigenically. Often, however, the fossils occur in such a way that we have cause to suspect that they appear in a rock deposited in an environment unlike that in which the limestone-forming organisms lived. It can be difficult to determine whether the fossils occur primarily or secondarily if neither they nor the remaining constituents of the rock show traces of transportation and resedimentation (see also below.)

There are limestones with authigenic macrofossils in all the series of strata in which larger rock-forming calcareous organisms play a prominent role or form a characteristic element. The Middle Cambrian limestones of Skåne contain abundant large carapaces of trilobites, as also the thick Lower Ordovician limestones, and the organisms (e. g. trilobites) from which these fragments originate, have lived in the environment in which the rock was formed. As the various calcareous parts of an animal (e. g. the cephalon, pleura, and pygidium of a trilobite) are not as a rule found together but scattered, a resedimentation of the fragments may have taken place after the death of the animal and the decomposition of its soft parts. Such resedimentation and transportation is natural within and in the vicinity of the littoral zone. We have an opportunity of observing it in accumulations and movements of mussel shells near present-day shores. The limestones mentioned, like countless others, show that a transportation takes place at somewhat greater depth, too. As the fragments are often embedded in fine calcareous mud, transportation, or rather scattering, must have taken place rather through occasional turbulence of the waters than through permanent currents, which would have prevented deposition of the mud together with the large fragments.

Fossils do not generally occur in situ in these limestones. Lamellibranchs, gastropods, brachiopods, etc., which appear in the same way as the trilobite fragments, have as a rule been moved in connection with deposition. On the other hand, certain organisms, and particularly those that have a heavy calcareous shell, are not infrequently found in situ. Stromatoporoids occur in stratified limestones, as in reefs, in the place and environment in which they have lived. The same is true of corals (especially *Tabulata* and *Heliolitida*) which appear in, for example, the Silurian limestones of Gotland, Jämtland, Skåne. Several of these corals are found in highly argillaceous, marly layers, and in them large and small cup corals (*Tetracoralla*) are also found undisturbed.

Limestone beds may be almost entirely composed of fragments of bryozoans or crinoids. Limestones of this type are particularly common in the immediate neighbourhood of reefs. The Gotlandian reefs are usually surrounded by stratified crinoidal limestones, and similar rocks occur near the reefs in the Ordovician of Dalarna. Bryozoan limestones of considerable thickness occur together with the coral reefs in the Upper Cretaceous of Skåne. On disintegration of the crinoids and bryozoans the fragments have been scattered about the place in which the organisms lived, but transportation has been so slight in general that there is reason to regard the fossils as largely occurring authigenically. Only rarely are bryozoan colonies with unbroken branches found embedded in calcareous algae or mud and thus preserved in situ. Here and there may be found the basal part (the root) of a crinoid still on its primary foundation, but extremely rarely are the stem and the calyx found undisturbed with it. It is only in marly layers deposited in quiet water that one finds fragile calcareous organisms of this type preserved unbroken.

It is hardly necessary to underline that a limestone bed may contain some authigenic and some allotigenic macrofossils. Heavy calcareous bodies can have lain relatively undisturbed in one place whilst lighter ones (thinner shells) have been moved to the same place by transportation from another environmental area. The mixing of authigenic and allotigenic fossil material is of especial interest when the latter is of a different and greater age than the former. This condition is found in sediments which are partly composed of previously deposited but later resedimented material. During stirring-up and washing-away of the fine matter in earlier deposited layers, negative sedimentation, the macrofossils may under favourable circumstances remain and be mingled with remains of the organisms which were alive when the denudation was taking place. The older fossils will through this resedimentation appear in a foreign environment; those originating from the resedimentation period, on the other hand, occur authigenically, unless they, too, have been subjected to longish transportation before deposition. Often it is the older, secondarily resedimented and accumulated fossils which are predominant, as will be more clearly shown below.

Many of the macrofossils found in marine sediments deposited at fairly great depth originate from animals which lived and moved in the surface layers of the seas. The remains which have sunk down to the bottom (fish-bones, sharks' teeth, otholites, etc.) may be authigenic in spite of the fact that they belonged to organisms which perhaps could not have lived in the environment in which the sediments were formed. The presence of these fossils need not complicate interpretation of the formation of the sediments, since the character of the fossils gives the explanation for their appearance. When, as is sometimes the case, fossil remains are found in these sediments of benthogenic animals belonging to other areas, e. g. littoral shallow-water areas, the problem of the relation between their occurrence and the formation of the sediment becomes less clear. As these animals have not had the ability to move freely for any great distance, their transportation has been wholly dependent on external circumstances, and it may just as well have taken place after the death of the animal (and after the primary deposition of the calcareous fragments) as during its lifetime. It is most accurate to designate fossils of this kind as allotigenic. As an example, it might be mentioned that floating-grass attached to mussel shells can float for these long distances and make possible deposition of the shells in areas where the animals do not live.

As can be seen from the foregoing, the macrofossils may be authigenic without being preserved in the place and situation which the organism adopted when it was still alive (in situ). To interpret the environmental conditions under which the animal or the plant lived or the sediments were formed, it is of the greatest value to be able to determine whether the fossils occur primarily or secondarily.

Limestones with allothigenic or secondarily resedimented macrofossils.

It has been pointed out above that macrofossils may after transportation, e. g. by floating, have been secondarily deposited in an environment foreign to the organisms. In other cases negative sedimentation may have entailed such far-reaching resedimentation that the fossils can no longer be considered authigenic. This condition becomes particularly remarkable, as has been mentioned above, when remains of an older fauna become mingled with representatives of a younger.

Mostly, however, resedimentation is not very extensive. It may be restricted to the material deposited during a relatively short space of time. The result is then merely a rearrangement of the various constituents of the sediment and possibly washing-away of the more fine-grained parts and at the same time accumulation of the coarser. If the primarily deposited sediment consists of calcareous mud with embedded macrofossils, the latter may be accumulated at a certain level. They will then be included as a particularly highly fossiliferous band in a bed rich in calcareous mud if the latter is stirred up without being washed away, but they will form a coarse, possibly conglomerate-like upper part of a bed if the stirred-up finer material is washed away. Fossil accumulations of this type are extremely common in marly limestone series rich in macrofossils. In many cases one is fully justified in calling these rocks "fossil conglomerates" (HADDING 1956).

If the mud is washed away during resedimentation and the coarse inclusions (macrofossils etc.) are kept in motion for a lengthy period of time, the latter come to be worn in the same way as the pebbles in a normal conglomerate. The rock created in this way has the character of an intraformational conglomerate and should be so called, even if the pebbles consist exclusively of fossil fragments. In certain series of strata the calcareous pebbles-fossils are coated with a crust of calcareous algae, in others with a thin layer of glauconite (see HADDING 1932 and 1956). In both cases wear has been reduced or stopped completely after the pebbles received their coating. Further wear may, however, have taken place before they were embedded or covered by a deposit of more fine-grained matter.

Fossil conglomerates and intraformational conglomerates of the type shown above have their most characteristic development when the macrofossils consist of less brittle calcareous bodies such as cup corals, small *Heliolitida,* stromatoporoids, and calcareous algae, but thick mussel shells and brachiopod shells may also give rise to similar rocks. If the macrofossils consist chiefly of thin, brittle shells or fine-branched and other easily broken calcareous bodies, limestones of another type arise on resedimentation of the material. Even if the fossils were primarily deposited relatively undamaged and embedded in mud, they become broken during any resedimentation and more or less finely crumbled. One may use the term "fragment limestones" for all the limestones with a high content of fossil fragments. In a number of cases the fragments have been worn smooth, in others chemically or organically (by algae) corroded, but they are often found just as sharp-edged and unaffected as if they had been embedded and conserved in direct connection with crushing and disintegration.

Fragment limestones may be found in all the series of strata with calcareous macrofossils, and in Sweden they are well represented in the Middle Cambrian, Ordovician, and Silurian, and not least in the Senonian deposits. The relatively mudfree coquina and micrococquina limestones of Skåne are of considerable thickness and distribution. Sometimes (in certain places) the fossils are found undamaged (cf. HADDING 1933, pp. 54 and 67), but as a rule they are crushed. In limestones they occur with size-separated material. Attention is here drawn to the fact that Sweden has Quaternary deposits of similar character. The post-Glacial shell beds on the west coast of Sweden (Bohuslän) are composed of more or less resedimented shells, principally lamellibranchs. Like the Cretaceous coquina beds, they have been formed near a rocky shore under conditions especially favourable for the development of abundant organic life of a certain character. The Quaternary shell beds have, however, been lifted above the surface of the water at an early stage, and they have therefore not had the transportation, separation, and stratification which distinguish the Cretaceous coquina limestone.

Limestones composed essentially of microfossils and microfragments.

It is generally impossible to identify macroscopically the fine-grained or dense material in limestones, whether it is found as a matrix between large fossils or as the major mass of the rock. Diagenetic change and cementation of the mass make it difficult to distinguish the constituents, even if they are so big that, if they were isolated, they could be observed with the naked eye and studied with a magnifying-glass.

Under the microscope these fine-grained limestones are found to be composed partly of small fragments of large fossils, partly of more or less whole microfossils and at the same time of calcareous mud of indeterminate character. In certain limestones or certain beds the fragments or microfossils are predominant, in others the mud.

The microfossils which appear as rock-formers have often lived as plankton. Exactly similar plankton organisms can be found in the sediments of the modern seas, particularly in the Globigerina mud. Here, as in the fossil sediments, the foraminifers play the most important role. They are not very well represented in the Swedish series of strata, however. There they never occupy the greater part of a limestone. They occur most profusely in the Upper Cretaceous (Senonian and Danian) of south-west Skåne. No equivalents are found in Sweden of the large, profuse, and really rock-forming types of the Fusulina and Nummulites limestones.

In the Swedish Paleozoic limestones there are abundant small molluscs and crustaceans which can only be seen under the microscope. They are particularly profuse in certain levels. They have a characteristic development, which may enable them to be of importance as index fossils. It has, however, been beyond the scope of the author's task to go into this question by investigating and identifying the extensive material. In several cases certain zones of Sweden's Middle Ordovician have been followed from place to place with the aid of various microfaunae which are characteristic of them.

More considerable in quantity in the Swedish sediments than the relatively well-preserved microfossils are the extremely small calcareous fragments which appear under the microscope as a characteristic and predominating constituent of the majority of fine-grained and dense limestones. These limestones are formed at less depth than those mentioned above with a marked plankton fauna, but they have been deposited at greater depth and in quieter water than the coarser fragment limestones. It is certainly not inaccurate to ascribe limestones composed of these microfragments to an outer zone surrounding the one in which the real fragment limestones were deposited. Also of importance is the sedimentation of calcareous mud which has taken place in shallow lagoons with the assistance of algae and bacteria (see also below).

The microfragments are often more highly corroded by chemical dissolution than the larger fossils (fig. 35, p. 53). The reason may be that they have been transported a greater distance and have been kept in suspension for a longer period than the larger and heavier fragments.

Just as the macrofossils lie embedded in finer material, the larger microfragments are surrounded by smaller ones. In addition to these there is a calcareous mud of more indeterminate character, which, however, is certainly chiefly composed of the most fine-grained fractions of the crumbled fossils.

Among the fine-grained limestones the author has put several into a separate class under the designation "nodular limestones". These are characterized by great abundance of small round or rounded, usually hazily circumscribed calcareous grains, sometimes visible to the naked eye, sometimes microscopic (figs. 6 and 7). Small fossil fragments may occur between the grains. The grains are composed of a white, cryptocrystalline calcite mass, which is very light-absorbent in transmitted light, for which reason the grains appear opaque in rock-slices. They are of relatively uniform size in the fine-nodular limestones (fig. 7), and it appears reasonable to regard them as accumulated small coprolites. But in the somewhat coarser rocks the nodules are grown into each other in a way which can scarcely be reconciled with this interpretation. The coarsest nodules, which vary greatly both in shape and size, cannot be coprolites. To regard the nodules as diagenetically solidified mud-lumps, which have been accumulated together with small fossil fragments,

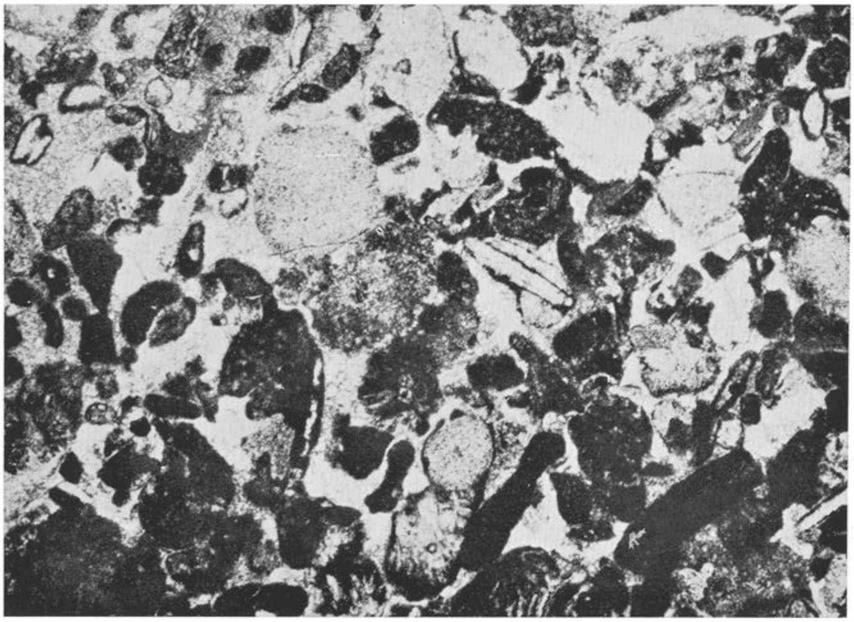

Fig. 6. Fragment limestone with algal nodules. Högklint group. Visby, Gotland. (Prep. 6487, photo 1415.) — 20×.

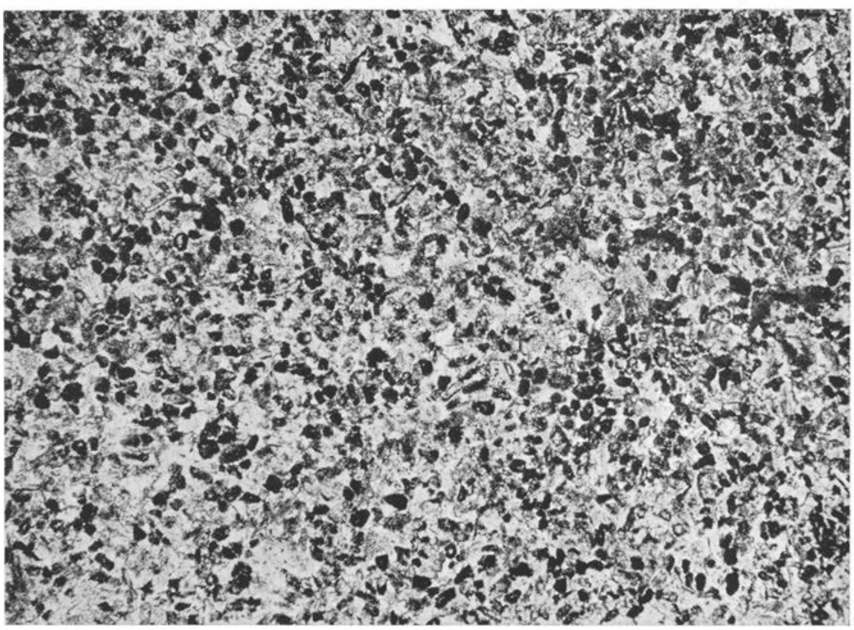

Fig. 7. Fine-nodular limestone. Slite group. Västerhejde, Gotland. (Prep. 2078, photo 1426.) — 20×.

would not be defensible, since the matrix of the rock, the mud, has been changed during diagenesis into a clearly crystalline, transparent calcite. The cryptocrystalline texture and apparently opaque character of the nodules, however, naturally carry one's thoughts to the calcareous algae which occur abundantly in the same limestone series (see also HADDING 1958).

The calcareous mud of limestones.

All limestones, with the exception of the coarse-grained ones with particularly well-separated material, contain a greater or lesser quantity of fine calcareous mud. In some limestones the mud forms the matrix of the rock. Under the microscope the mud is often found to be composed of profuse small fossil fragments of the kind illustrated above. But there also exists mud which is mainly composed of small calcareous bodies (of a different nature), usually 1—3 μ large. They may be seen completely unaffected by diagenesis, and in certain cases, e. g. in chalk, they can easily be isolated from one another. It is nevertheless difficult to establish their character and formation. The author has already touched upon this problem (HADDING 1933) in connection with a discussion of inorganic, marine limestone-formation and of the importance of bacteria in limestone-formation, and it will therefore suffice to refer to this discussion.

The calcareous mud may also be composed of fragments crushed to such a fine powder that it is impossible to identify it as remains of certain larger calcareous bodies. During periods and in areas with formation of fragment limestones in thick series this type of mud may also be expected. The better the fragment material has been separated according to coarseness, the more probable is it that very fine mud of this kind has also been deposited. It is quite natural that this calcareous mud is mixed with argillaceous detritus, which has required the same conditions for deposition. Both the inorganic, chemically precipitated and the bacterially formed calcareous mud, however, may have been deposited in areas with little or no supply of argillaceous mud. The absence of considerable quantities of argillaceous detritus in a limestone gives reason for suspecting that the calcareous mud of the rock is authigenic; a higher clay-content, on the other hand, shows that it has been secondarily formed through crushing of shells and other calcareous bodies.

As examples of both these types, the author might mention chalk and pure forms of coccolite limestone on the one hand and certain Gotlandian marlstones on the other.

A particular type of mud limestones have dense texture, conchoidal fracture, flat bedding planes. They may be called, after a known rock, lithographic limestones or lithographic shale. Although the author has not come across any rocks in Sweden which conform entirely with the lithographic shale of Solnhofen, there are limestones of similar development, and a few words will be devoted to them.

The dense, hard, compact, cream-coloured limestone of Solnhofen is composed of calcite crystals, on the average 3 μ (0.003 mm) large. In test sections of normal thickness (0.02 mm) the individual grains appear indistinctly, and the rock is found to be a dense, blurred or diffusely granular mass. Nuances are found, however, in the absorption of light.

Of the same composition is a limestone which occurs in thin beds of the Lias series at Weston (Somerset, England). Calcite crystals, which are transparent individually but seem very light-absorbent when overlying one another (average size about 3 μ) form nodules and blurred masses which are surrounded by somewhat larger crystals. Structurally this rock is uniform with the lithographic shale from Solnhofen. Colour, hardness, fracture, and other macroscopic qualities are also alike.

Other macroscopically dense, microscopically crystalline rocks with grains 1—3 μ have been observed by the author in various places in Russia: in the Lower Senonian at Ananour in Georgia, also in the Lower Senonian at Goitk station in west Caucasia, and in the Miocene (Sarmatian) at Izer Bash in Dagestan. Flat bedding surfaces, conchoidal fracture, and light colour are points in common between these rocks and the Solnhofen rock. The three rocks, however, contain small foraminifers, which are filled with calcite crystals.

Swedish limestones which most closely approach those mentioned above as regards the nature and development of their constituents, are certain limestones in Gotland. — Dense, thin-bedded, light yellowish-brown limestones belonging to the Slite group (south-east of Visby) and the Högklint group (north of Visby) have flat bedding planes and conchoidal fracture like the lithographic limestone. Under the microscope they are found to be composed of a microcrystalline calcite with grains 1—10 μ, and hazily circumscribed cryptocrystalline flocks or nodules. (See textural forms p. 46.) The latter have been interpreted by the author as flocks of calcareous algae. The adjacent crystalline calcite mass is probably recrystallised calcareous mud, primarily formed bacterially (see also HADDING 1958).

Inorganically precipitated $CaCO_3$ — Aragonite.

The lively discussion which has gone on with regard to the possibility or the extent of purely inorganic formation of calcium carbonate will not be gone into here. The author has not found anything in the pre-Quaternary limestones of Sweden which can help to clarify this question. The diagenetic transformation which these limestones have undergone has largely obliterated the primary nature of the calcareous sediments, and one cannot expect any mud which may possibly have been precipitated in a purely chemical manner to have retained any distinctive mark. A chemical precipitation of $CaCO_3$ in the form of aragonite would recrystallize (to calcite) in a short time. There is no possibility of finding the aragonite preserved in the Paleozoic and Mesozoic limestones.

Dolomite.

Chemical analyses show that the Swedish Paleozoic and Mesozoic limestones are remarkably poor in magnesia, MgO. On the other hand, dolomite and dolomitic limestone are found in several places among the metamorphic pre-Cambrian sediments. They will not be discussed here.

Crystals of dolomite have been observed in glauconitic limestone. There the dolomite crystals appear as a metasomatic transformation of glauconite grains. Siderite and particularly calcite also occur in a similar way.

The non calcareous constituents of limestones.

Next to calcium carbonate argillaceous matter, arenaceous detritus, and to a lesser degree glauconite, phosphorite, and silica are present as rock-forming or otherwise important constituents of limestones. As non-rock-formers a number of minerals occur, e. g. pyrite, barytes, and iron hydroxides.

Argillaceous matter in limestones.

The clay-content of limestones is very variable. In the purer limestones, in which the $CaCO_3$-content reaches 97—99 %, the content of $Al_2O_3+SiO_2$ may drop to less than 0.5 %. We find numerous limestones of this type in the Danian of Skåne and in the Silurian of Gotland, the former as coccolite, bryozoan, and coral limestones, the latter as fragment limestones. The argillaceous matter in these rocks is difficult to observe in the beds (fig. 8), unless it is accumulated in small lumps or lenses. Argillaceous or rather marly layers occur, however, between the pure limestone beds, which can be interpreted as evidence of a change in sedimentation: a temporary decrease in the deposition of calcium carbonate or a great increase in the deposition of argillaceous detritus, generally, however, a combination of the two.

Even in the pure limestones with very low clay-content the argillaceous minerals are mixed with quartz, but in such fine-grained form that it cannot be distinguished even microscopically. Whilst the weight-ratio of SiO_2 to Al_2O_3 is 1.2 in pure kaolinite and somewhat higher in kaolin clays,[1] it goes up very considerably in the argillaceous matter of certain limestones. The table below shows this ratio in a few Swedish rocks.

SiO_2- and Al_2O_3-content of "pure limestones".

	$CaCO_3$	SiO_2	Al_2O_3	SiO_2:Al_2O_3
Coccolite limestone, Limhamn (Danian)	98.9	0.18	0.03	6.0
» » » »	97.0	0.80	0.02	40.0

[1] Analyses of refractory clay from Höganäs have given the values 2.2 and 1.6.

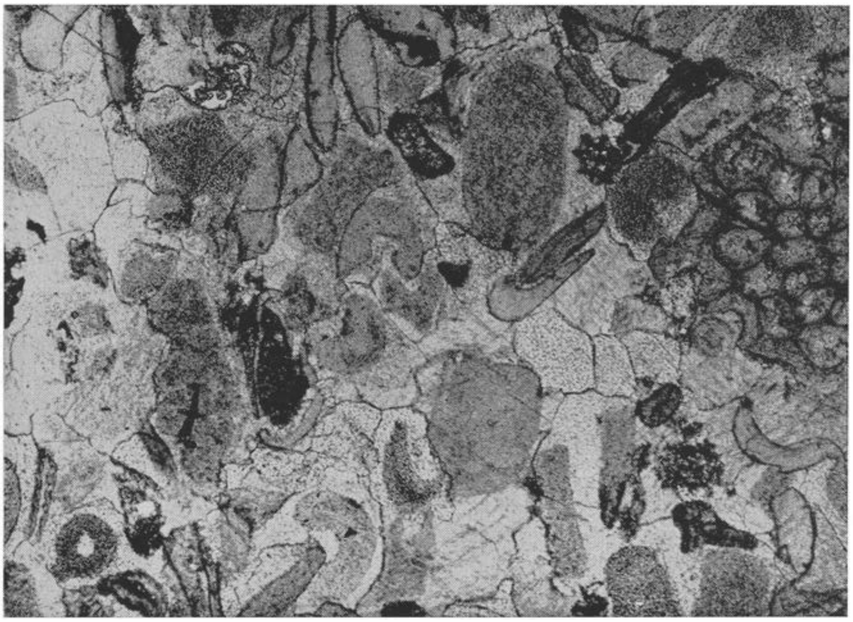

Fig. 8. Pure, crystalline fragment limestone. Slite group. Smöjen, Gotland. (Prep. 7406, photo 1524.) — 20×.

	$CaCO_2$	SiO_3	Al_2O_3	SiO_2:Al_2O_3
Bryozoan limestone, Limhamn (Danian)	98.9	0.55	0.03	18.3
Coral limestone, » »	97.8	0.72	0.10	7.2
Fragment limestone, Smöjen (Silurian)[1]	97.46	1.03	0.47	2.0
» » Bungenäs »[2]	97.1	0.78	0.48	1.6
» » Kappelshamn»	97.4	0.9	0.5	1.8

It is clear from the table that the ratio of SiO_2 to Al_2O_3 in the Silurian limestones is the same as in a normal kaolin clay and that no surplus of free silica is therefore to be reckoned with in these rocks. The ratio is very different in the Danian limestones. All of them have a clear surplus of SiO_2, varying from 3 to 20 times the normal content bound up with Al_2O_3. There need be no doubt about the character of this silica: it consists of a siliceous impregnation in the limestone or possibly partly of fragments of siliceous sponges. Pronounced siliceous impregnations and flint pebbles and beds occur abundantly in these limestones, and they trace their origin to primarily interstratified siliceous sponges. Silica in the form of grains of quartz has not, however, been observed as a normal inclusion.

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[1] General analysis of whole boatload of limestone.

[2] Average value of 29 analyses.

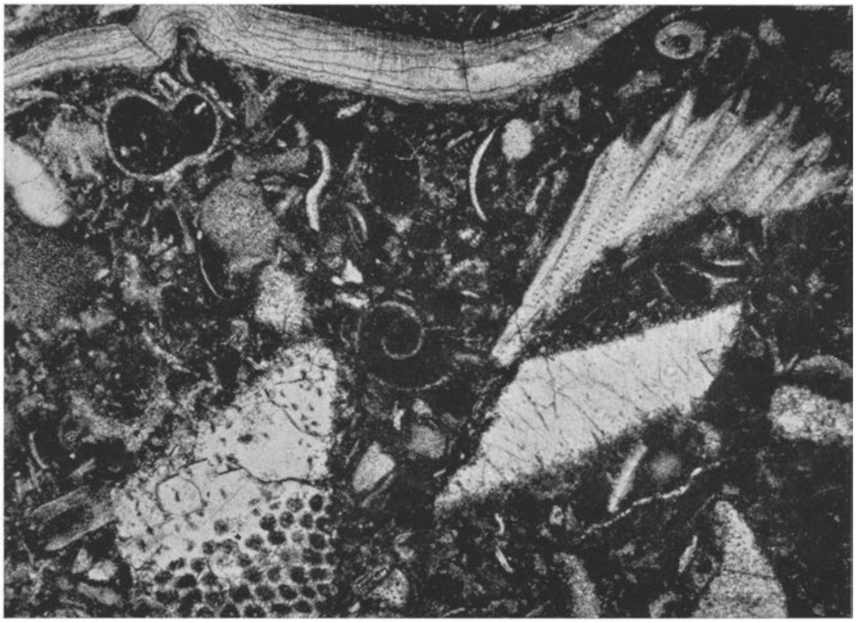

Fig. 9. Argillaceous fragment limestone. Slite group. Valleviken, Gotland. (Prep. 3531, photo 1373.) — 20 ×.

The less pure limestones (fig. 9) with a $CaCO_3$-content of 65—85 % have, of course, a greater content of material indissoluble in dilute hydrochloric acid, particularly SiO_2, Al_2O_3, and Fe_2O_3. The ratio between the first two is somewhat variable, as appears from the adjoining table.

SiO_2- and Al_2O_3-content in less pure limestones.

			$CaCO_3$	SiO_2	Al_2O_3	SiO_2:Al_2O_3
Ceratopyge limestone,		Flagabro, Skåne	81.8	8.4	2.8	3.0
Planilimbata	»	Köping, Öland	66.9	13.6	3.5	3.8
Limbata	»	Torslunda, »	85.7	4.2	1.3	3.2
Orthoceras	»	Fågelsång, Skåne	80.5	11.4	2.2	5.2
Expansus	»	Utby, Dalarna	84.9	2.7	1.45	1.8
Fragment	»	Lickershamn, Gotland	79.8	11.2	3.2	3.1
Oolitic	»	Burgsvik, Gotland	85.4	10.2	1.0	10.2

The large surplus of SiO_2 in the oolitic limestone from Burgsvik is explained by a relatively abundant admixture of grains of quartz in the rock. In none of the remaining limestones has it been possible to show the presence of free silica microscopically.

In marly limestones and marls the ratio of SiO_2 to Al_2O_3 has been found to be similar to that of the above-mentioned limestones, thus generally between 3.0 and 4.0.

The argillaceous element of limestones is not macroscopically noticeable when the Al_2O_3-content is less than 1 % and the argillaceous matter is finely divided. With a higher clay-content a light greyish-blue, greyish-green colour is seen, which, however, gives way to red, brown, or yellow if the rock contain Fe_2O_3 in noticeable quantity (>1 %), or to dark-grey or dark-brown if the limestone contains bitumen.

Silica.

Silica occurs in limestones partly authigenically as chalcedony or quartz, partly allotigenically as detrital quartz.

Authigenic silica is found partly concretionarily accumulated as flint pebbles, partly scattered as impregnation in and as metasomatic replacer of calcite aggregates (fig. 10). The large quantities of flint in Senonian and Danian limestones have been explained as having been formed in connection with dissolution of siliceous sponges, which were abundant in these sediments. The extensive silification of certain Ordovician rocks (e. g. Chasmops limestone in Västergötland) has taken place in the immediate neighbourhood of pyroclastic layers (bentonite). In some cases it has been impossible to establish the origin of the silica, which was deposited from circulating solutions in water.

Detrital quartz is present in greatly varying quantities. It is an essential constituent of arenaceous limestones (fig. 11) but is completely absent in many others, both fine-crystalline or dense and coarse limestones.

The grain-size generally reflects the conditions under which the sediment was deposited. Coarse, well-rounded grains of quartz are a natural element in conglomeratic limestones and coquinoid rocks. Small angular or subrounded quartz grains are typical of several impure limestones. Above corrosion-surfaces detrital quartz is found together with allotigenic glauconite grains. Eolian quartz can be traced in sediments belonging to an environment foreign to other detrital quartz.

Felspar and other detrital minerals.

Together with quartz other detrital minerals, too, are sometimes found in limestones, particularly felspar. If the limestone has been formed in the immediate vicinity of brecciated or weathered granite or gneiss, it may contain splinters or worn fragments of these rocks (Ceratopyge limestone, Dalarna; Chasmops limestone of the Lockne field, Jämtland; Senonian coquina limestone, Skåne).

Of inorganic fine-detritus apart from argillaceous matter only negligible quantities of mica and chlorite have been observed.

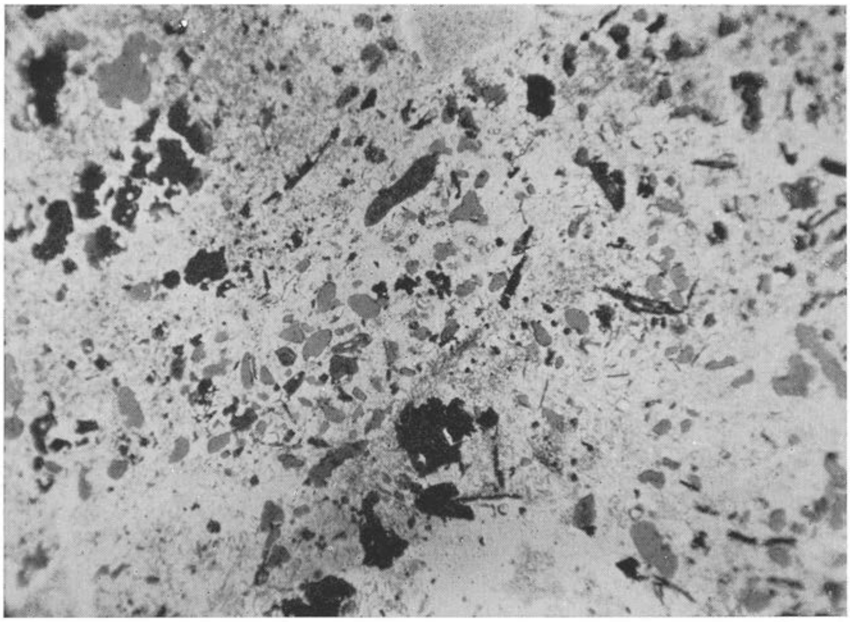

Fig. 10. Silicified, glauconitic limestone. Middle Cambrian. Brantevik, Skåne. (Prep. 8909, photo 1751.) — 20×.

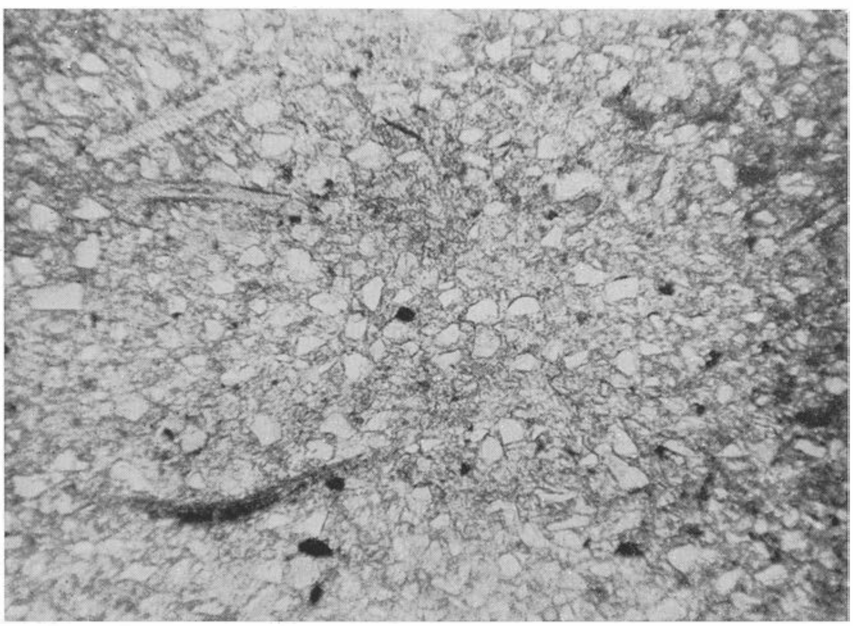

Fig. 11. Arenaceous limestone. Middle Cambrian. Äleklinta, Öland. (Prep. 7518, photo 1459.) — 60×.

Glauconite.

Swedish limestones are to a large extent glauconitic. This is particularly true of the Lower Cambrian and Lower Ordovician limestones. Beds or bands rich in glauconite are characteristic of certain zones or stages, whilst others are without glauconite throughout.

The glauconite occurs partly authigenically (particularly as impregnation on corrosion-surfaces, etc.), partly allotigenically in the form of larger or smaller grains. In both cases the glauconite gives a lead to interpretation of the conditions of formation of the limestone (see HADDING 1932).

Phosphorite.

Like glauconite, phosphorite is found in limestones in certain parts of the Swedish series of strata (Lower and Middle Cambrian, Lower Ordovician, etc.); other parts are almost completely without phosphorite (e. g. the Silurian of Gotland, the Danian of Skåne).

Phosphorite occurs authigenically and allotigenically in limestones, almost exclusively in glauconitic beds. The conditions of formation have thus been to a certain extent similar for the two minerals. In contrast to the phosphatic nodules which we know from the bottom of modern seas, the Cambro-Ordovician nodules have been formed in shallow water. They occur most abundantly in arenaceous limestones and calcareous sandstones. The nodules encountered in non-arenaceous limestones generally contain grains of quartz, and they thus appear secondarily.

Authigenic phosphorite in limestones may form diffuse masses (fig. 12) or occur as infilling in or crust on fossils. This type of phosphorite is found in beds with abundant phosphatic brachiopod shells. The phosphate precipitated in connection with the formation of the Cambro-Ordovician limestones originates in part at least from phosphatic shells. In certain cases, e. g. in the origin of the large, continuous phosphorite lumps in (fossilfree?) Lower Cambrian calcareous sandstone, the source of the phosphate must be sought elsewhere.

Diagenetic and metasomatic minerals.

Limestones always contain a certain if small amount of iron, generally noticeable as a red, yellow, brown, or green pigment, or in the presence of certain ferruginous minerals (pyrite, siderite, glauconite, and chamosite).

In the marine limestones dealt with here the ferruginous matter has usually been supplied to the sediment in connection with its formation.[1] It may, however, have

[1] Secondary infiltration of ferruginous water, which has brought about rhythmical precipitation of ferric hydroxide, has been observed.

Fig. 12. Phosphatic nodule with crust of calcite and phosphorite. Ceratopyge limestone. Flagabro, Skåne. (Prep. 6316, photo 1292.) — 20×.

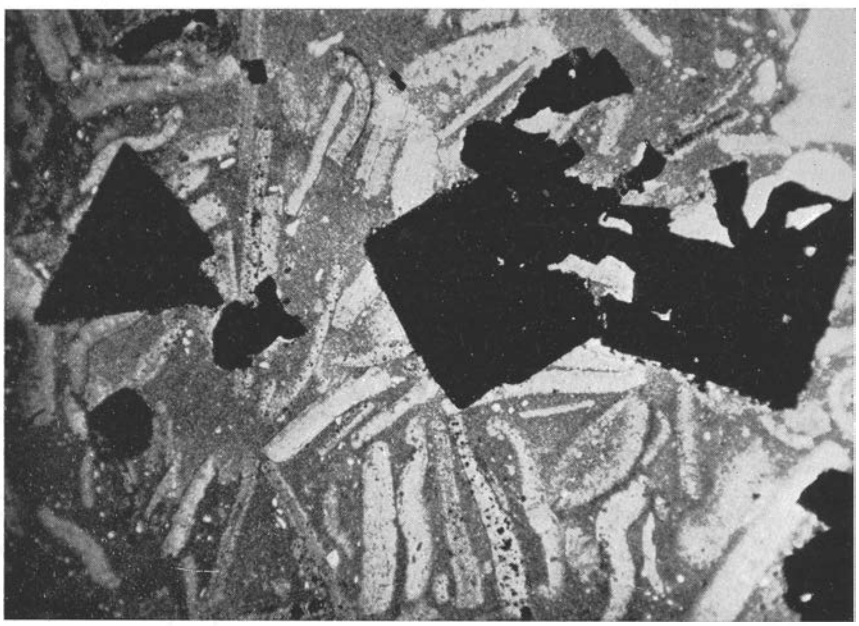

Fig. 13. Pyrite: crystals, aggregates, and dust. Fragment limestone. Lower Cambrian. Hardeberga, Skåne. (Prep. 8760, photo 1731.) — 20×.

undergone changes during diagenesis. Iron sulphide precipitated primarily as powder may have crystallized diagenetically as pyrite or have been oxidized to iron hydroxide; ferrous carbonate and silicate may have been oxidized to ferric oxide. These changes have been followed by colour changes. The Lower Ordovician limestones, in particular, offer examples of how drastic these changes can be. On corrosion-surfaces the colour changes from green to yellow and red without the iron-content being noticeably altered. The origin of the different colours will be discussed in another context.

Pyrite occurs in practically every part of the Swedish series of strata, least in the pure algal and fragment limestones, most in the argillaceous or bituminous limestones. The mineral generally takes the form of small cubes or round, concretionary aggregates (fig. 13). Only in isolated cases have larger lenticular aggregates or black pulverous impregnations been observed in limestones. Marcasite crystals are not found in the rocks studied.

Limonite forms a characteristic element of some Ordovician limestones. The mineral occurs in brown, opaque, partly oolitic grains, as infilling in small shells (gastropods, ostracods) and as impregnation in porous fossils (pelmatozoan fragments, fig. 124, p. 166).

Siderite has been observed as a metasomatic mineral in glauconite (HADDING 1932, pp. 16—21).

Chamosite occurs sparingly and only in a few cases in the limestones mentioned here. The mineral takes the form of greyish-green ooids.

Barytes has proved on a systematic study of Swedish limestones to occur in several parts of the series of strata. The mineral is encountered in Cambrian bituminous limestones as well as in Ordovician red fragment limestones and grey marly limestones (fig. 109, p. 142, and fig. 167, p. 224). In these sediments the barytes appears in the form of clear crystals, sometimes skeletal. Transformation to calcite can be traced in some rocks (cf. HADDING 1938).

Strontianite has been observed in isolated cases (see HADDING 1938).

Cordierite (iolite) occurs as pseudohexagonal triplets surrounded by calcite in argillaceous limestone from the Ordovician of Västergötland (fig. 182, p. 242). The mineral may be regarded as metamorphic, and formed when a dolerite magma penetrated the sedimentary series of strata.

Structures.

With regard to structure limestones can be roughly divided into stratified and non-stratified. To the latter belong principally the reef limestones. The stratified limestones are composed of clastic material of varying coarseness. The Swedish reef limestones have been dealt with earlier (HADDING 1941), and in the following, therefore, only the structure of the stratified limestones will be discussed.

Stratification.

The vast majority of calcareous sediments are clearly stratified, but the stratification appears with varying clarity. Certain coarse fragment limestones (coquinas) and pure calcareous muds (chalk) may have thick portions with scarcely noticeable stratification. Other coarse calcareous sediments (calcareous conglomerates) may, like dense ones (e. g. lithographic limestones), be markedly stratified. There are several reasons for these factors.

Causes of stratification.

There is no space here for a thorough discussion of the origin of stratification of limestones, but by means of examples from the Swedish series of strata the author will illustrate the three principal causes, namely: 1) change in the sedimentary material, 2) change in the speed of sedimentation, and 3) denudation of already deposited sedimentary layers. These three main causes of stratification may be combined two and two or all three. Denudation, for instance, cannot take place except in connection with a change in the speed of sedimentation, but the latter change need not necessarily entail any denudation. The stratification arising out of variations in the material transported to the place of sedimentation and there deposited appears unequivocally in the series of strata. Diagenesis has little obliterating effect on this sort of stratification, since the diagenetic processes cannot bring about any change in the chemical or mineralogical composition of the material. If a calcareous stratum is deposited with an admixture of, for instance, coarse grains of sand, this stratum will always be distinguishable from surrounding strata with no or more fine-grained arenaceous admixture. It is not necessary, however, for this sort of stratification to be marked by bedding planes or be otherwise obvious: the strata may largely consist of uniform material and be intimately allied with each other. But as a rule an appreciable change in the sedimentary material brings about pronounced stratification and well marked bedding planes, e. g. in limestone beds, in shale, or argillaceous and marly layers between limestone beds, etc. Rhythmically alternating deposition of dissimilar material gives rise to the most pronounced form of stratification occurring in sedimentary series of strata (see p. 38).

Variations in the material, in its mineralogical composition and coarseness are mostly caused by changes in the strength of the means of transportation. In marine series coarser and finer grains, like specifically heavier and lighter ones, supersede one another in sedimentation according as the strength of the current allows their transportation to and deposition in a certain area.

The constituents of the various strata are always instructive of the cause of stratification. In many cases it is found that the change in the constituents and the stratification have been caused by other factors than those indicated above, e. g. chemical precipitation or organic sedimentation, caused by variations of temperature or altered physical-chemical conditions in the sedimentation basin. "Spontaneous" and large accumulations of plankton organisms (foraminifers, coccolites, etc.) as well as temporary flocculation of inorganic compounds (glauconite etc.) give rise to stratification with changes in material without the latter being directly ascribable to variations in the transportation conditions.

Stratification arising from variations in the speed of sedimentation would seem to be common in certain series of strata and particularly in monotonous shales, but it is generally difficult to establish the cause of it. With completely continuous sedimentation of uniform material it is not possible for marked strata and beds to be formed, if diagenesis (compression, dehydration, and recrystallization) keeps pace with sedimentation. If, however, for one reason or another, deposition occurs for a certain time at a varying, faster or slower, pace, the relation between deposition and diagenesis is disturbed. This disturbance gives rise to stratification, especially in the case of a great slowing-down or cessation of deposition for some time. During the interval between two periods of normal sedimentation a surface or a belt is created, which by its texture, colour, richness in fossils, etc. betrays a change in continuous deposition. In calcareous sediments stratification of this type occurs inside the beds. The planes which border the beds have, however, been formed in connection with changes in the nature of the material.

Stratification arising from denudation of already deposited sediments can often be demonstrated in series of strata. The method of formation is most obvious when some part of the denuded strata has remained as pebbles in an intraformational conglomerate or when the denudation has resulted in a distinct corrosion-surface. Both these forms of stratification occur in limestone series, and the corroded bedding planes are particularly common. Very often they have been formed in connection with a variation in the sedimentary material.

Stratification may also arise through denudation without the formation of intraformational conglomerates or distinctly corroded bedding planes, and in fact this method of formation is probably extremely common. If deposition of calcareous or argillaceous mud takes place in quiet water, a temporary periodical turbulence of the water will prevent deposition of the suspended mud, and if the turbulence is sufficiently strong, part of the already deposited and not yet consolidated mud will be stirred up. Stirring-up may continue until a diagenetically consolidated surface manages to resist the turbulence of the water. If the consolidated portions are also denuded, a conglomerate is formed, as was mentioned above. However, the denudation may also stop before all the loose mud has been stirred up or washed away. In such cases it is difficult or impossible to give an exact account of the course of formation, since the result is largely the same as in the case of slowed-down or periodically interrupted sedimentation. Accumulation of fossils may occur even in the case of a temporary, minor washing-away of mud, but in limestones it usually requires such extensive denudation that the accumulation of fossils aquires the character of a conglomerate, the formation of which is in no doubt. A stirring-up of already deposited mud often creates uneven, out-thinning beds. Gaps in the series of strata caused by denudation are not usually so great that they can be demonstrated paleontologically-stratigraphically, but on the other hand they are so general that they have a great influence on the thickness of a zone or formation.

In reef limestones a strata-like structure may be formed if the reef-building organisms have a pronounced tabular form. Examples of this have earlier been given by the author from the stromatoporoid- and coral-rich reefs of Gotland (Hadding 1941, p. 50 etc.). In normally sedimented calcareous matter without reef-building organisms, on the other hand, structural forms may arise recalling those of the reefs inasmuch as stratification is absent or indistinct in limited parts of the series of strata. The parallel arrangement of the material may be more or less clear, but there are no bedding planes. This form of calcareous sediment, lenticular limestone, consists of calcareous lenses or irregular calcareous lumps arranged parallelly or irregularly distributed in loose marl. On the whole, though, the stratification of the series of strata is clear enough from the continuous, extended limestone beds which occur together with the lenticular limestone. Fine examples of this type of limestone are found in the Silurian series of Gotland and in several places in the Ordovician of Sweden, too. The hard calcareous lumps and lenses often contain fossils as cores, but are otherwise composed of diagenetic calcite, chiefly of concretionary nature (cf. p. 50).

Development of bedding planes.

The bedding planes of limestones have acquired different appearances according to the mode of their formation, the nature and variation of the material. Since a bedding plane in marine sediments has always at a certain stage been the surface of the bottom of the sea, one might expect the bedding plane to be a detailed picture of the primary sediment surface. This is not, however, the case.

In the loose, watery mud no bedding planes are formed primarily of the coarsely rough, uneven type found in limestone beds (fig. 14). These planes are not formed either during corrosion or washing-away of mud. Bedding planes of this type are found particularly well developed where the limestone beds are interstratified by shale. The limestone beds then have upper and lower surfaces similar in character, i. e. equally pitted or gnarled. Similar rough planes can also be found inside limestone beds. The origin of the roughness, unevenness, is explained if we examine certain argillaceous limestones of knobby texture. In these the characteristic unevenness is not only found on the bedding planes but unchanged throughout the whole bed. We also find that the unevenness has its origin in the occurrence of closely packed, irregular, hard calcareous knobs separated by looser, marly portions (fig. 15). Formation has occurred diagenetically in such a way that the calcium carbonate of the deposited mud has crystallized about certain scattered centres and that at the same time the argillaceous mud has partly been displaced so that it has come to lie as a matrix around the calcareous lumps. The course of diagenesis in marly

Fig. 14. Rough bedding surface. Limbata limestone, Lower Ordovician. Hällekis, Västergötland. (Photo 1501.) — $^1/_1$.

Fig. 15. Knobby bedding surface. Orthoceras limestone, Lower Ordovician. Uddagården, Västergötland.

calcareous mud is practically always like this (see p. 50). If the calcareous mud only contains a small quantity of argillaceous matter, the calcareous lumps coalesce into a dense bed. Here more or less distinct traces of the original scattered calcareous lumps are found only in the rough surface of the bedding planes, particularly at the boundary with argillaceous layers.

The bedding planes have a different appearance if the calcareous mud has not been transformed diagenetically into the above-mentioned form. In certain dense, pure limestones formed of mud (e. g. the lithographic limestones) the bedding planes are smooth. In other dense limestones, e. g. Danian limestones, the bedding planes are uneven. They have an irregularly undulated cross-section, which has arisen as a result of diagenetic crystallization and consolidation about sparsely scattered centres or under the influence of concretionarily formed flint pebbles in or between the beds.

In the forms described above the bedding planes have arisen without corrosion or other appreciable denudation. But extremely common also are bedding planes modelled by chemical or mechanical action before they were definitively covered by younger sediments. Corrosion-surfaces are far from always conspicuous as bedding planes, but when they are, their character is very distinct. The cup-shaped, pit-shaped, or crack-like depressions are gently rounded (fig. 16), but with sharply protruding shell fragments and other hard portions (fig. 17). As corrosion occurs in connection with a break in sedimentation or a change in it, the constituents of the overlying bed are somewhat different from those in the corroded bed. Corrosion, even chemical, is connected with an increased turbulence of the water. Liberated mud is washed away and more coarse-grained matter is deposited on the corrosion-surface — bedding plane (fig. 147, p. 198).

Many sediments have bedding planes covered with fossils. If the latter are very light types, e. g. graptolites, their accumulation may have been due to reduced mud-deposition, in turn due to reduced supply or delayed deposition. If the fossils are heavier types, e. g. macrofossils of coarse calcareous structure, accumulation on the bedding plane in relation to the remainder of the bed has occurred in connection with a washing-away of the fine-grained matter, calcareous or argillaceous mud, which normally surrounded the fossils. Thus in the latter cases the bedding plane has been formed in connection with a partial denudation of the deposited sediment, through negative sedimentation (cf. HADDING 1927, p. 86). If the negative sedimentation has been extensive, the accumulated material becomes worn. The external shape of the fossils may have been completely obliterated, and the material then consists of greatly rounded fossil fragments (cf. HADDING 1956). The accumulated, more or less worn material may grade over into the undisturbed layer below without a sharp boundary, in which case the bedding plane may be more clearly marked above the coarse, possibly conglomeratic part of the bed.

Relatively smooth and flat bedding planes occur on arenaceous limestone and calcareous sandstone, even if the beds are separated by argillaceous or marly layers. In these rocks diagenesis has not resulted in the formation of calcareous lumps of

Fig. 16. Corrosion surface — bedding surface. Glauconitic Ceratopyge limestone. Köping, Öland. (Photo 1504.) — $^1/_1$.

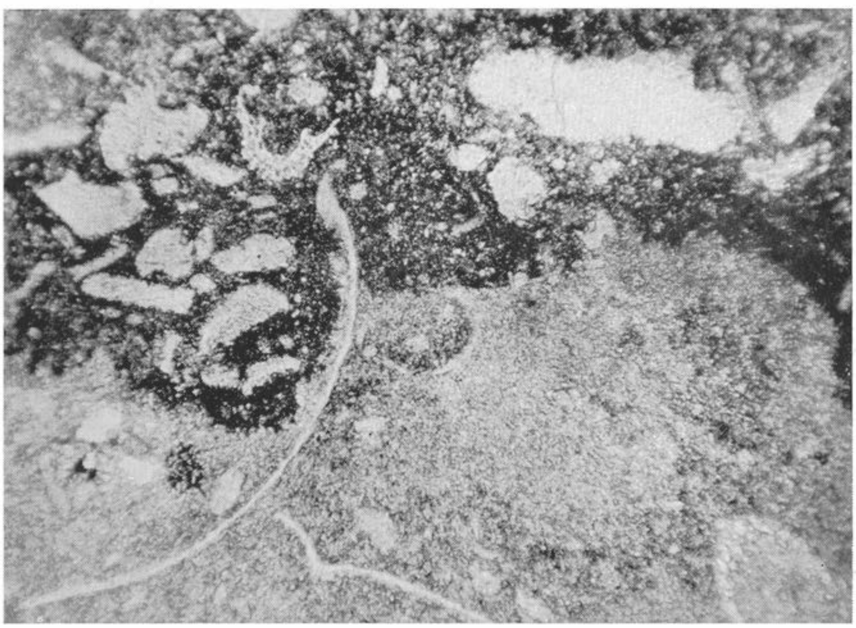

Fig. 17. Corrosion surface with protruding shell fragment. Limbata limestone, lower part yellow, upper red. Köping, Öland. (Prep. 6924, photo 1334.) — $60\times$.

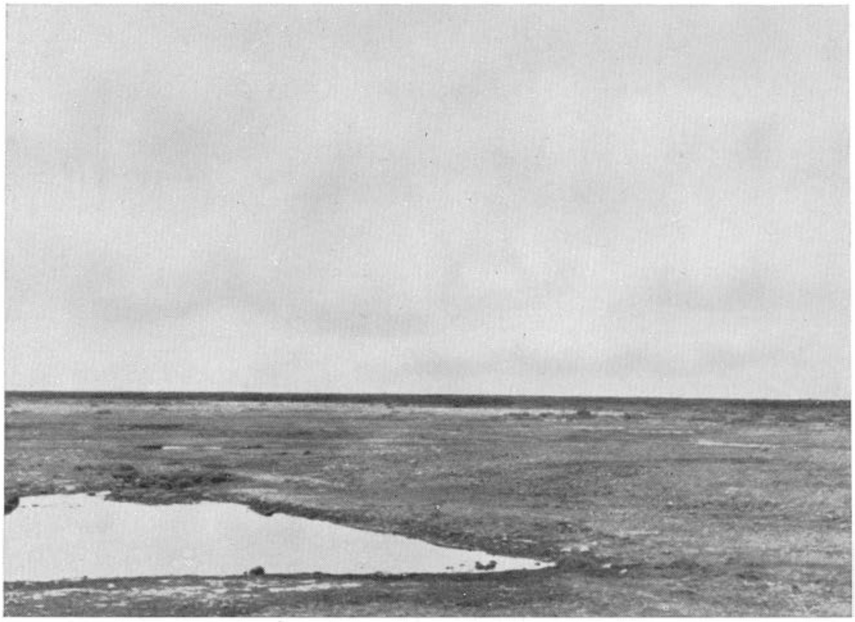

Fig. 18. Extensive beds of Orthoceras limestone. Alvaret E. of Resmo, Öland.

the kind described above, but the rock has been cemented with larger or smaller calcite crystals. A similar condition is found in many fragment limestones and also in certain argillaceous limestones, particularly the thin-bedded ones.

Limestones sometimes display tracks and markings but not by a long way so often as sandstones and arenaceous shales. Worm-tracks have often been observed, e. g. in the Orthoceras limestone of Öland. Ripple marks and desiccation fissures are rare. It is easy to confuse the cracks not infrequently seen on corrosion-surfaces with desiccation fissures. The former may have arisen submarinely as a consequence of diagenetic crystallization.

Extent of strata.

In certain series of strata the layers are very extensive. In the Ölandian Orthoceras limestone for example, it is possible to follow a bed for several hundred metres (fig. 18). At the same time it is found that the thickness of the beds has not undergone any appreciable change, which means that the strata must be assumed to have an extent far exceeding the area in which they could be traced. The similar development of, for example, the Limbata limestone over the whole distance from Ottenby to Horns udde (approx. 140 km), the even stratification, the flat (though rough) bedding planes, give us reason to believe that the individual beds in this part of the series of strata have an extent of several kilometres.

However, it is only necessary to go to the immediately underlying zone to find great variations in the series of strata with rapidly out-thinning beds. Negative sedimentation has alternated with positive. The limestone beds are often much corroded, and glauconitic sand and intraformational conglomerates indicate that strong turbulence of the water has caused the thinning-out of the calcareous sediments. However, even in this part of the series of strata one finds uniformly thick, extensive beds.

In other limestone series all the beds may take the form of thin, flat, usually uneven lenses. Whether they lie embedded in marly matter or cover one another directly, they indicate disturbances of the sedimentation.

In limestones with coarse matter (fossil fragments and conglomerates) cross-bedding occurs in places. Fine examples of this structure are found in the fragment limestones deposited between the reefs in the Silurian of Gotland (see Hadding 1956).

Thickness of strata.

The distance between bedding planes in a limestone bed may vary between wide limits. In chalk and coquina limestone one may encounter portions of one or several metres' thickness without any distinct bedding plane. In dense, even-grained limestones the thickness of the layers may go down to less than 10 mm. Apparently uniform, thick beds can, however, often be split along well developed bedding planes which were scarcely noticeable in the unaltered rock. When exposed to weathering, however, such beds fall apart into thin layers. When judging the worth of the various beds as building-stone, it is of importance to study their qualities in this respect, i. e. their hidden bedding planes.

A series of strata which in one place consists of relatively thick beds, may in another area consist of thin layers, for obvious reasons. A certain order between thinner and thicker beds can generally, however, be followed over wide fields. Within limited areas index strata may sometimes be characterized just as well by their relatively greater or lesser thickness as by their lithological nature.

Rhythmic bedding.

In limestone series one occasionally finds rhythmic bedding as pronounced as in varved clay. This rhythm may consist in the compact limestone beds being regularly divided up by more or less distinct changes in colour or composition. In other cases limestone beds of fairly uniform and generally small thickness alternate with likewise uniform layers of marl (fig. 19). Rhythmic bedding must be ascribed either to periodicity of the factors determining precipitation of the calcium carbonate or to periodicity in the transportation and deposition of argillaceous matter. Generally, however, a combination of these two possibilities can have been operative. Ultimately, regular climatic changes have probably caused the rhythmic

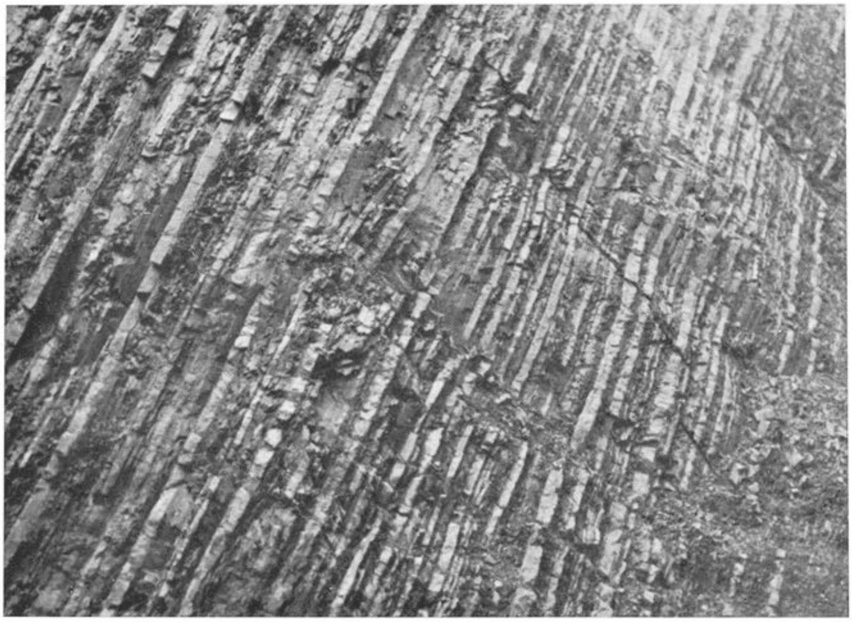

Fig. 19. Rhythmic sedimentation: limestone and marl. "Cement limestone". Upper Llandoverian. Styggforsen, Boda, Dalarna.

variations in the sediments. To judge the length of the climatic periods from the thickness of the layers, is extremely hazardous. The regularity of rhythmic sedimentation and repetition in a very large number of strata inevitably make one think of annual stratification. An annually returning rainy period with washing-out of mud and simultaneous sweetening of the sea-water in a sedimentation basin, alternating with a dry, warm period with little supply of mud, increased temperature, increased evaporation, and more abundant deposition of calcium carbonate would undoubtedly result in an alternate sedimentation of limestone and marl as rhythmic as in the series of strata under discussion. It is difficult to accept that the regularly returning changes occur at intervals of decades or centuries, since the series lack environmental change. Changes in local conditions should have occurred during a long period of sedimentation and been clearly noticeable in these sediments, which were deposited in relatively shallow water.

The regularity of rhythmic sedimentation, not disturbed by environmental changes, speaks decidedly for an interpretation of the strata as annual layers.[1] However, the thickness of the strata argues against this interpretation. Black has calculated (1933, p. 461) that in the Bahamas, where the deposition of calcium carbonate is very considerable, the annual sedimentation is up to 0,166 mm. After dehydration and crystallization the stratal growth is scarcely likely to exceed 0,1 mm. The

[1] de Geer 1941.

calcareous series illustrated here have beds with a thickness of approx. 110 mm and would therefore have required a period of 1.000 years for their formation if the speed of sedimentation was as great as that of the Bahamas. Where the mud-content is greater and the argillaceous layers thicker (the series of strata reproduced in fig. 19 have by and large equally thick argillaceous layers and calcareous beds, each approx. 20—50 mm), the speed of growth becomes to a large extent dependent on the supply of mud. The argillaceous particles in both the calcareous beds and the marly layers have a diameter of approx. 0,001 mm. In the marly layers, however, they are greatly mixed with grains of quartz, 0,01—0,02 mm in diameter. The argillaceous layers have thus arisen during periods with a supply of relatively coarse detritus, the calcareous layers during periods with only very fine mud. In both cases, however, the matrix of argillaceous matter is so fine-grained that deposition cannot have resulted in layers of several centimetres' thickness being formed during one year.[1]

Despite the fact that assumption of annual stratification would give a simple explanation of alternating sedimentation, it is difficult to adhere to it. It presupposes abnormally rich deposition of both calcium carbonate and clay, which is almost unthinkable in the case in question. A rhythmical variation of several hundred, perhaps a thousand years would be more probable, and if we had known of something of the sort, the author would not have hesitated to see in it the cause of the formation of, for example, the "Cement limestone" of Dalarna.

In connection with a discussion of alternating sedimentation the relation between series which display such sedimentation and series which are more uniform should be elucidated. The series of alternating limestone and shale at Styggforsen in Dalarna illustrated above belongs to the Retiolites shale, i. e. to the middlemost part of the Silurian. It occurs directly adjoining a marly series of shales ("Sphaeroid shales") with scattered, interstratified, calcareous concretions but without any suggestion of alternating sedimentation between limestone and shale. The shales of the two series, which are entirely similar from a lithological point of view, show that they were formed under the same environmental conditions. Deposition of calcium carbonate has taken place during the whole of the deposition period, but only in the formation of one of the series has it been rhythmically increased, so that actual calcareous beds have been formed. In various places in Dalarna one finds Retiolites shale in the form of alternating limestone and shale, but in other areas (Skåne, Västergötland) only as marly shale. Why does alternating sedimentation occur only in a limited area, when the material and environment do not seem to present any obstacle to a

[1] If suspended argillaceous mud of the coarseness we find in the series of strata dealt with was sedimented at a speed of ten argillaceous particles per second on each mm^2, the annual result would be a compact layer of less than 0,3 mm thickness. A layer of 30 mm would require 100 years for its formation. The speed of sedimentation is, however, unknown; it may very well be less than was assumed above. On the other hand, the argillaceous particles are not closely packed; the rock is fairly loose and marly. To determine the length of time required for deposition of the argillaceous layers from their thickness is as hazardous as to determine the time required for formation of the calcareous beds.

more extensive formation? And why does it occur only during a limited period, when the requirements were there for its formation during a much longer period? The data available to the author do not permit any conclusions regarding these questions, but the cause of the variations between the different areas must be sought in local differences, and possibly even variations in one and the same place may be due to locally changed conditions for deposition of calcium carbonate.

Calcareous concretions in argillaceous and arenaceous sediments.

Cementation of sand by calcite is common. In many cases, however, it has been obliterated by dissolution of the calcite cement and its replacement with silica. Concretionary accumulations of the dissolved calcium carbonate circulating in the sand play a very small role in arenaceous sediments. The author has previously mentioned cases of such concretions from the Keuper strata of Skåne and refers to the description then given (Hadding 1927, pp. 100 and 162).

In argillaceous sediments calcareous concretions are quite a common phenomenon, but they are not always found where they are expected. They may occur in slightly calcareous shales but be missing in more highly calcareous ones. In series of strata of similar composition the calcite may occur in the form of concretions in one place, as calcareous bands in another; no obvious reason can be shown for the different development. The concretion-like calcareous lumps of lenticular limestones are mentioned in connection with the account of the stratification and texture of limestones (see pp. 32 and 50). The calcareous concretions occurring more sporadically in argillaceous sediments generally have a different development, a more regular shape. In Sweden they are restricted to the Cambro-Silurian and principally to the alum shale and other black, bituminous shales. Less frequently they are found characteristically developed in marly shales, as for example in the "sphaeroid shale" of Dalarna.

Calcareous concretions in alum shale are always very bituminous and known under the designation of stinkstone or anthraconite. They may have a strikingly regular shape, a somewhat flattened rotation ellipsoid, but they are sometimes more shapeless, not infrequently because of coalescence of several concretions. The size varies from a few centimetres to more than one metre in diameter. Stratification can quite often be seen, and the bedding planes can sometimes be followed out into the surrounding shale. (Regarding anthraconites in Swedish sediments see also p. 92.)

Stylolites.

Typical stylolites are seldom found in the Cambrian and Ordovician limestones, but they are strikingly common and well developed in the Silurian. Their formation will not be discussed here, but their development and mode of occurrence will be illustrated with a few examples from Gotland. Stylolites are common in the fine-

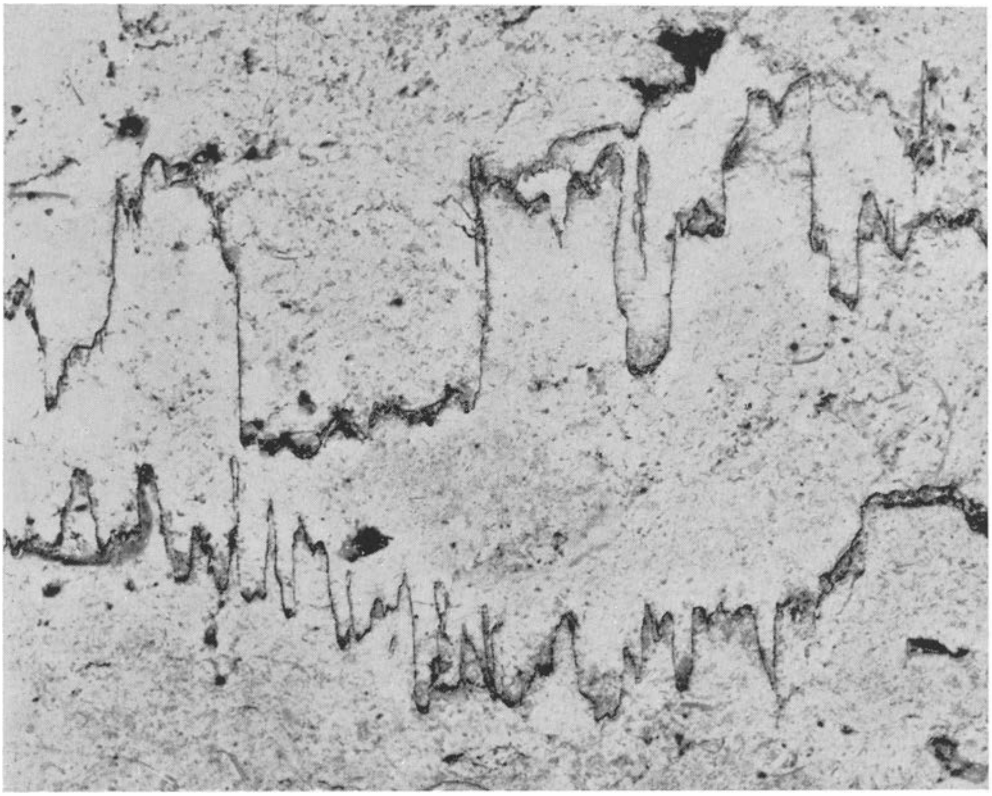

Fig. 20. Stylolites in pure, fine-grained fragment limestone. Slite group, Wenlockian. Storugns, Gotland. 5.5 ×. Foto. J. von Feilitzen.

crystalline, pure, even-bedded limestones of the Slite group. They have not been observed in coarse fragment limestones, but occur in some cases in reef limestone. The individual "sutures" run independently of one another (fig. 20). In less even-grained beds and reef limestone the "sutures" are irregular in direction; they may even cross one another.

Deformed calcareous sediments.

Calcareous sediments have often been stirred up by turbulent currents. The result may be that shells and fragments have been embedded without orientation in the matrix (see fig. 88, p. 118). In some limestones, however, a bedding occurs which has arisen during sliding of the sediment. The more or less clearly tabular fossil fragments are arranged concentrically or in a stream-lined fashion (fig. 123, p. 166 and fig. 45, p. 68). In certain cases the fragments are confused in a way that indicates strong general and irregular turbulence in the unconsolidated sediment (fig. 49, p. 72).

The texture of calcareous sediments.

Calcareous sediments have to a large extent been basically transformed from a textural point of view during diagenesis. Recrystallization of the primarily deposited calcium carbonate can be traced in the majority of limestones, and often it has obliterated the original texture. This factor must be taken into account in a survey of the textural forms of calcareous sediments, and a definite distinction must be made between primary texture and secondary or diagenetic texture. Only the former is of interest for judging the conditions of sedimentation and primary character of calcareous sediments.

Primary textures.

Primary texture occurs in limestones which display little or no diagenesis and in those which owing to their primary peculiarities can be recognised in spite of diagenetic processes. To the latter forms belong earthy, granular, nodular, and conglomeratic textures, fragment textures, oolitic and stromatolitic textures. Also primary are the textural features occurring in various calcareous sediments characterized by organic remains, e. g. bryozoan, foraminiferal, algal limestones, etc.

Conglomeratic texture.

Large, more or less rounded fragments of limestone or limestone-forming organisms may form a major part of a calcareous bed (fig. 21 and fig. 176, p. 236. Also HADDING 1927 and 1956). Even if diagenesis has affected both the pebbles and the matrix, the conglomeratic character has nevertheless been preserved. It is easy to distinguish the texture of these rocks from that found in calcareous sediments with diagenetically formed calcareous pebbles in an argillaceous or marly mass.

The conglomeratic texture gives evidence of denudation of earlier-formed calcareous sediments. Sometimes the conglomerate can have been formed simply by washing-away of mud and fine grains with accumulation of the large fossils which lay embedded in the mud. Fossil conglomerates of a similar kind can also arise if large limestone-forming organisms are washed together. Beds of cup corals, tabulates, bryozoans, and brachiopods often belong to the former type, crinoidal limestones sometimes to the latter.

Fragmental texture.

To indicate that a limestone is largely composed of more or less fragmentary limestone-forming organisms, the term fragment limestone, coquina or microcoquina limestone is used in this work. The texture displayed by these rocks can sometimes be justifiably called conglomeratic, but not in other cases. As a term for these I would suggest fragmental texture (figs. 22 and 23).

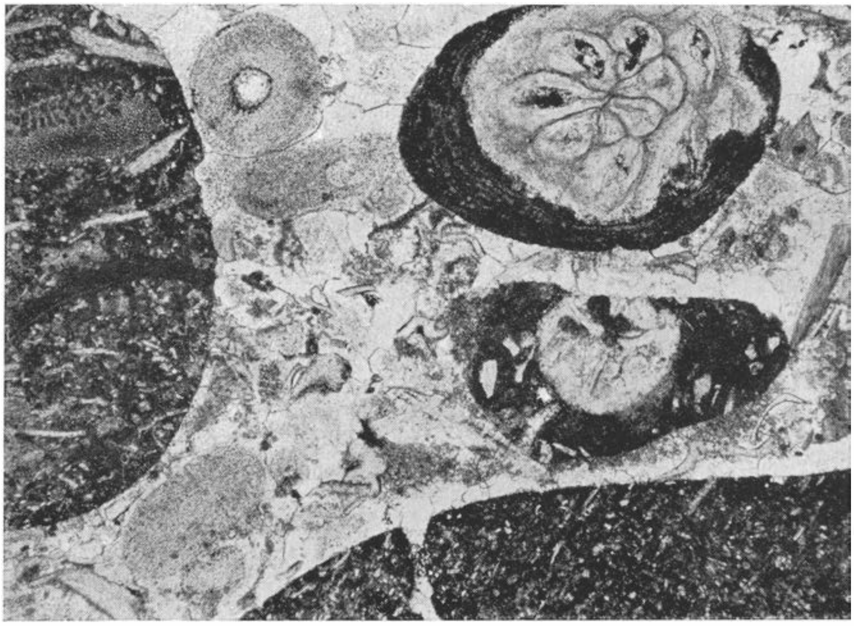

Fig. 21. Conglomeratic fragment limestone. Pebbles partly with algal crust and core of fossil fragment. Slite group. Valleviken, Gotland. (Prep. 6516, photo 1374.) — 20×.

Grainy texture.

Among recent sediments there occur accumulations of rounded calcite or aragonite fragments. These are best-known on the shores of coral islands, and they are called coral sand. Similar formations occur in fossil sediments, mainly composed of rounded fossil fragments (figs. 24 and 25). The primary form of the fragments has been obliterated, however, and the material appears as an accumulation of calcareous sand. The texture should therefore be distinguished from that occurring in fragment limestones and be called grainy texture.[1] However, a rock with this texture should, to avoid mistakes, not be called sandy limestone or calcareous sandstone but instead grainy limestone.

Muddy texture.

Calcareous sediments of muddy texture are composed either of pure calcareous mud, as in chalk, or argillaceous calcareous mud, as in marl. Where the sediments, as in the cases mentioned, are unconsolidated, it is not possible to point with certainty to any diagenetic transformation of the primary material. In marls, however, one often finds hard lumps formed through local recrystallization of the calcium

[1] Grainy texture is a special form of fragmental texture.

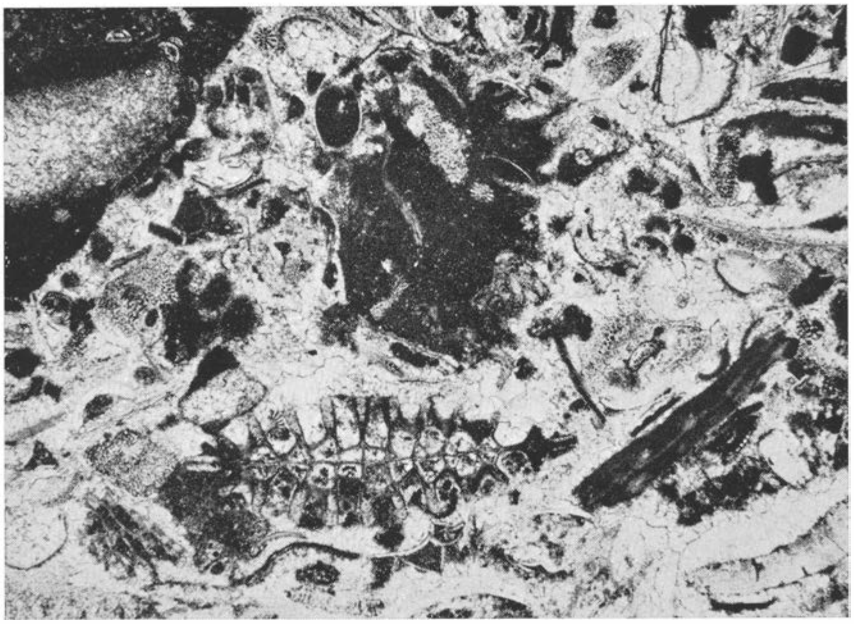

Fig. 22. Fragmental texture, coarse-grained. Fragment limestone. Upper Visby group, Llandoverian. Lickershamn, Gotland. (Prep. 6467, photo 1411.) — 20×.

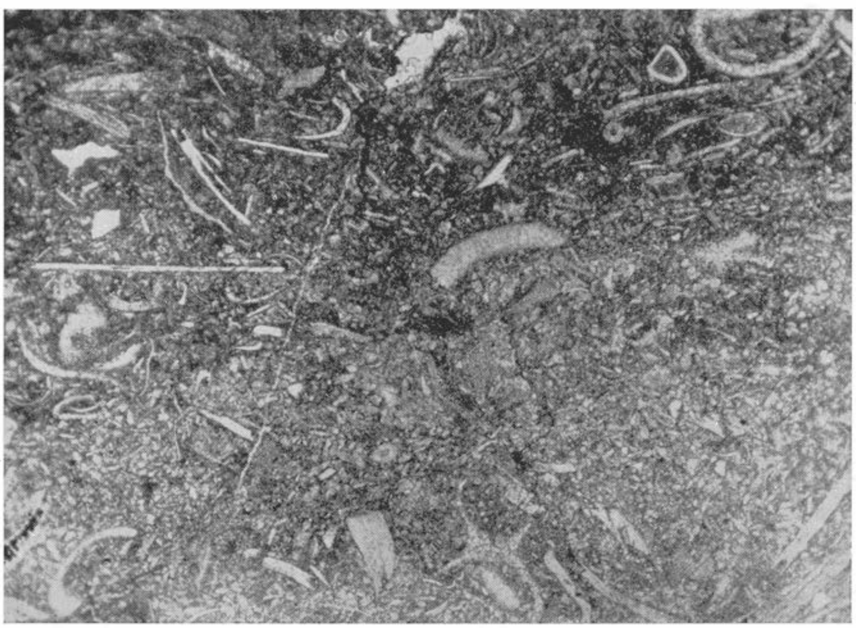

Fig. 23. Fragmental texture, fine-grained. Fragment limestone (microcoquina). Gigas limestone, Lower Ordovician. Brunflo, Jämtland. (Prep. 7144, photo 1618.) — 20×.

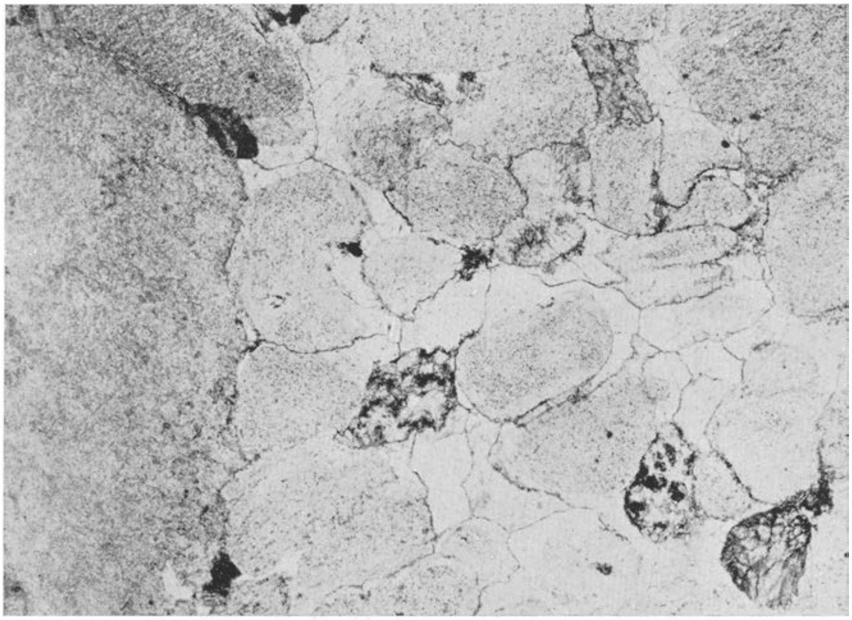

Fig. 24. Fragment limestone with grainy texture. Matrix strongly recrystallized. Slite group, Smöjen, Gotland. (Prep. 8216, photo 1561.) — 20 ×.

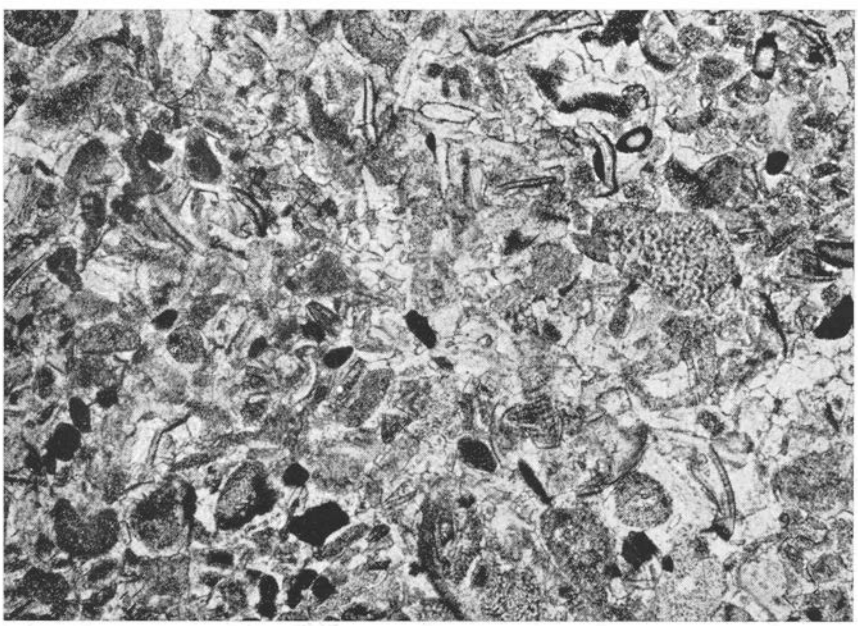

Fig. 25. Fine-grained fragment limestone. Asaphus limestone, Lower Ordovician. Hälludden, Öland. (Prep. 6925, photo 1409.) — 20 ×.

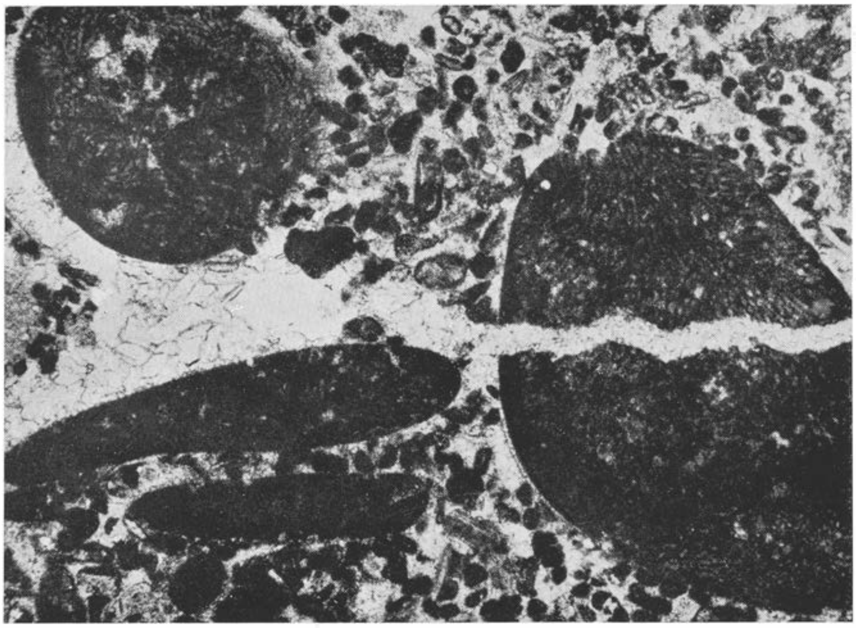

Fig. 26. Conglomeratic limestone, matrix with nodular texture. Algal nodules and pebbles. Högklint group. Visby, Gotland. (Prep. 6517, photo 1417.) — 20×.

carbonate in the mud. Primarily the sediment has had a uniform character and muddy texture in its entirety.

We can draw the same conclusion regarding dense limestones. These are affected diagenetically, but consolidation, which is a consequence of recrystallization, has not obliterated the original character of the mud. Dense texture is a diagenetic form, it is true, but the primary muddy texture of the rock is completely distinct. Amongst the argillaceous and silica-impregnated limestones, too, dense rocks occur with this same texture. To these belong, for example, the limestones occurring in the Ordovician of Sweden with a porous ("Backstein") texture appearing on weathering.

Nodular texture.

Certain bedded, macroscopically fine-grained or dense limestones are chiefly composed of small nodules, faintly reminiscent of oolite grains (ooids). Microscopically they prove to be hazily circumscribed, cryptocrystalline. They are surrounded by a fine-crystalline calcite matrix (fig. 26). The texture, which is typical of certain lagoonal limestones in the Silurian reef area of Gotland, has been interpreted by the author as having arisen through calcareous algae (Hadding 1958). The nodular texture becomes flocculent if the diffuse nodules more or less blend together.

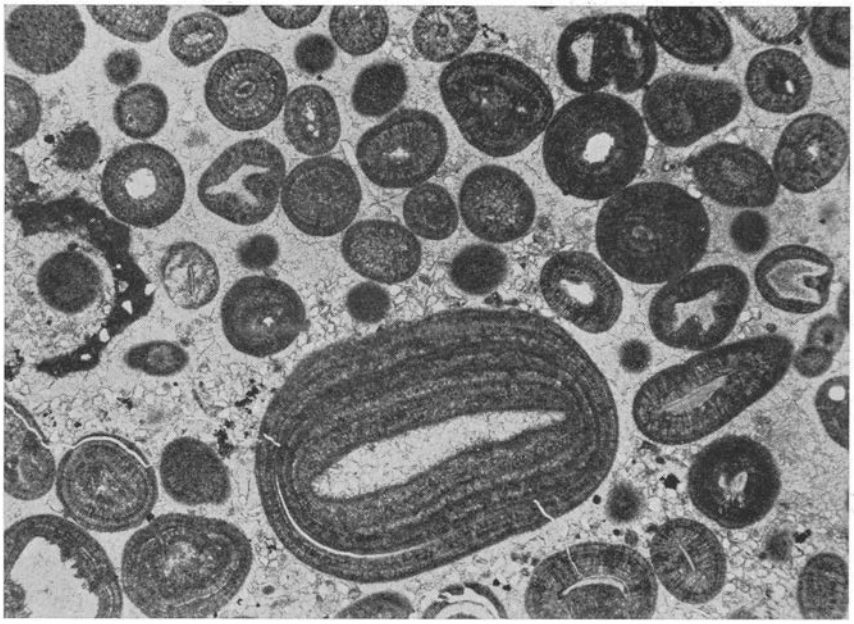

Fig. 27. Oolitic limestone. Burgsvik, Gotland. (Prep. 3337, photo 1388.) — 20 ×.

Flocculent texture.

Many of the macroscopically dense limestones are microscopically flocculent. They may be composed of extremely fine-grained, diffuse flocks in a clearly crystalline matrix. The flocks are sometimes clustered together like clouds or in irregular patterns (fig. 185, p. 245), sometimes isolated in small lumps or nodules. As this textural form has only been observed in diagenetically consolidated limestones, it is not at once apparent to what extent the structure is primary. The way in which diagenesis has altered the rock, however, gives us a lead in deciding its primary nature.

The flocks have hazy contours, it is true, but they appear clearly as inclusions in a fine-crystalline ground-mass. If they were secondarily formed, concretionary, they would, like other secondary calcite aggregates occurring in the rock, have been composed of larger crystals than the ground-mass (matrix). The grain size, however, is throughout smaller in the flocks than in the ground-mass The flocks must have been present in the ground-mass before its recrystallization began.

The flocks may have been formed as relatively solid calcareous bodies (by algae) which were embedded in the calcareous mud. They are genetically associated with the nodular algal limestones. It is certainly not out of the question for calcareous bacteria to have been active in the formation of the rock (Hadding 1958).

Oolitic texture.

Oolitic limestones or calcareous oolites are characterized from a textural point of view by the rounded, concentric grains which occupy a major part of the rock. These grains, the ooids, may be spherical, ellipsoidal, or more irregular in shape, often depending on the shape of the core around which the grains grew (fig. 27). Growth took place by deposition of new concentric crusts around those already formed. The concentric texture appears to a varying degree, however; it may sometimes be entirely smoothed out, especially if the ooids have acquired a pronounced radiated texture.

The oolitic texture is restricted to shallow-water sediments. In the Silurian strata of Gotland oolitic limestones occur together with sandstones, and they contain beds with ripple marks.

Several oolitic limestones have clearly been formed with the assistance of organisms, and in particular calcareous algae have been shown to be active. In their mode of formation the ooids of these rocks are of the same nature as the larger calcareous algal lumps (*Girvanella*, *Sphaerocodium*, *Spongiostroma*, etc.) which occur in the Gotlandian series of strata.

Stromatolite texture.

Stromatolite texture has not been encountered in the bedded limestones of Sweden and will therefore be passed over here. The textural forms characterizing reef limestones have been dealt with by the author in an earlier work (HADDING 1941).

Secondary textures.

The textural forms which arise in calcareous sediments during their diagenetic (and metamorphic) transformation are ali crystalline. They can be divided according to grain size into fine-crystalline and coarse-crystalline, according to crystal development into granular and radiated, according to distribution of the calcium carbonate into compact, spherical, lenticular, breccia-like, etc.

Crystalline-granular texture is typical of the majority of limestones of the hard, bedded type. This texture generally occurs in the matrix, too, of the above-mentioned limestones with preserved primary texture (conglomeratic, nodular, oolitic, or fragmental texture, etc.). The grain-size varies from a few thousandths of a millimetre to some millimetres. The grain-size may vary in one and the same bed, and often the boundary between portions of different grain-coarseness is clearly marked. An admixture of foreign matter may cause peculiar textural form, and this is particularly true if the admixture is bitumen. Mixed with argillaceous matter bitumen tends to appear as an irregular, flocculent interspersion in the calcite mass (fig. 28) or as a matrix around diffuse, round calcite grains (fig. 29). With a greater bitumen-content the bitumen is often displaced by the calcite crystals and lies as a matrix

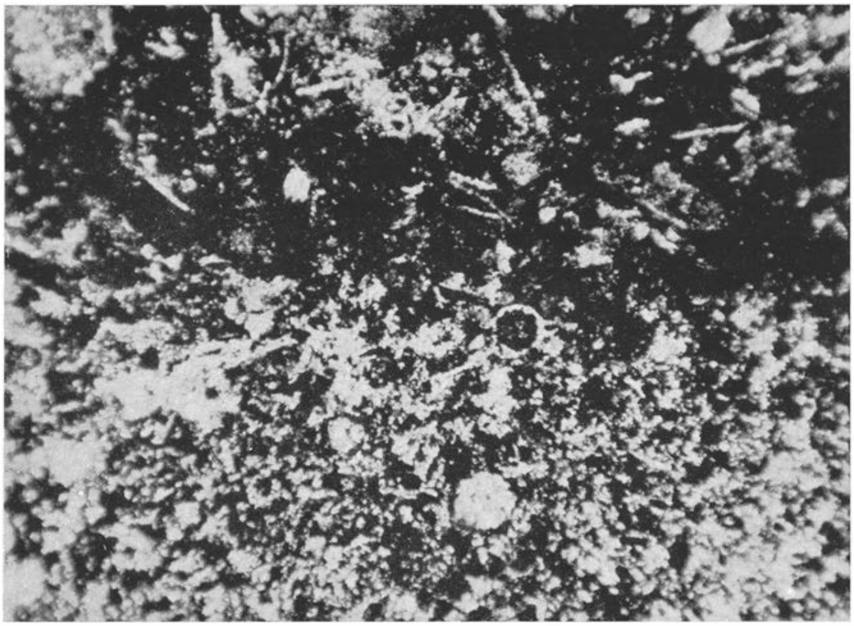

Fig. 28. Crystalline-granular texture. Orthoceras limestone, Lower Ordovician. Fågelsång, Skåne. (Prep. 6582, photo 1337.) — 60 ×.

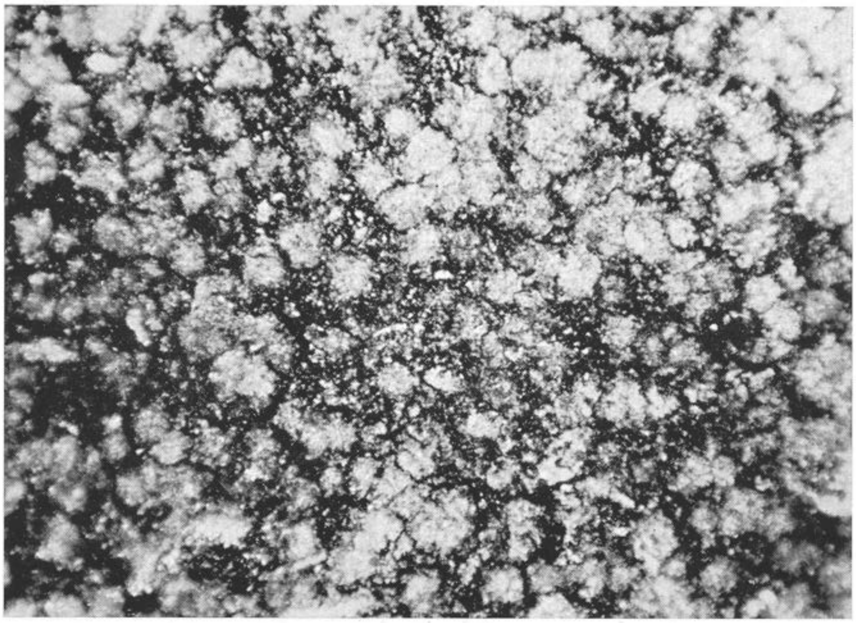

Fig. 29. Crystalline-granular texture. Orthoceras, Lower Ordovician. Fågelsång, Skåne. (Prep. 6585, photo 1338.) — 60 ×.

around them (fig. 30). The bitumen-content can also be restricted to small, scattered patches in the recrystallized rock, and these bitumen pockets are then surrounded by a relatively coarse-crystalline, generally radiated crust (fig. 31).

Columnar or fibrous texture. From a textural point of view the bituminous limestones are generally granular, but nevertheless one encounters fibrous forms amongst them oftener than in other limestones. Apart from the above-mentioned local radiated, secretion-like formations there occur concretion-like, fibrous portions with a bituminous matrix. The crystals are often divided up in a feather-like manner by enclosed bitumen (fig. 32). The columnar texture is best developed in the concretionary anthraconites, in which the calcite columns may attain a width of 10 mm and a length of more than 200 mm (see p. 96).

Dense, compact texture is characterized by an even distribution of the secondarily crystallized material in a limestone bed. The calcite and admixture of argillaceous matter, bitumen, fossil fragments, or arenaceous grains largely occur in the same quantitative ratio in sections parallel to the bedding planes. The variations found in sections at right angles to the bedding planes are caused by changes in sedimentation, and they have been further emphasized through diagenesis. — Compact texture appears in pure, dense limestones and in the matrix of most limestones of granular, oolitic, and fragmental texture. Many argillaceous limestones or limestones pigmented with iron hydrates also show compact textures, but it is not unusal for these to have acquired an accumulation of calcium carbonate in one form or another during diagenesis, with resulting special forms.

Lenticular texture is characterized by relatively pure, compact calcareous lenses enclosed in a marly, often loose mass (fig. 33). The lenticular texture is formed during diagenesis of very argillaceous calcareous mud by the concretionary accumulation of the calcium carbonate around separate centres, resulting in displacement of part of the argillaceous matter and its accumulation between the calcareous lenses. The lens can vary in size and shape, and the latter may sometimes motivate such textural terms as lenticular, spherical, or knobby texture (fig. 34). Sometimes the lenses, balls, etc. are arranged in distinct layers, sometimes they occur in such a way as to destroy the impression of stratification. The argillaceous or marly mass which separates them may occupy a greater or lesser part of the rock, and the lumps thus lie fairly closely packed or thinly scattered.

State of preservation of fossils.

The fossils in limestones have not as a rule been dissolved by the water which has circulated in the rock. Cavities left by dissolved shells, which are so common in the fossiliferous sandstones, seldom occur therefore in calcareous sediments. Where they are encountered, as for example in the coral limestone of the Danian of Skåne, the fossils have been composed of relatively readily soluble aragonite (see HADDING 1941, p. 120). Not infrequently, however, one finds mollusc shells etc. which show

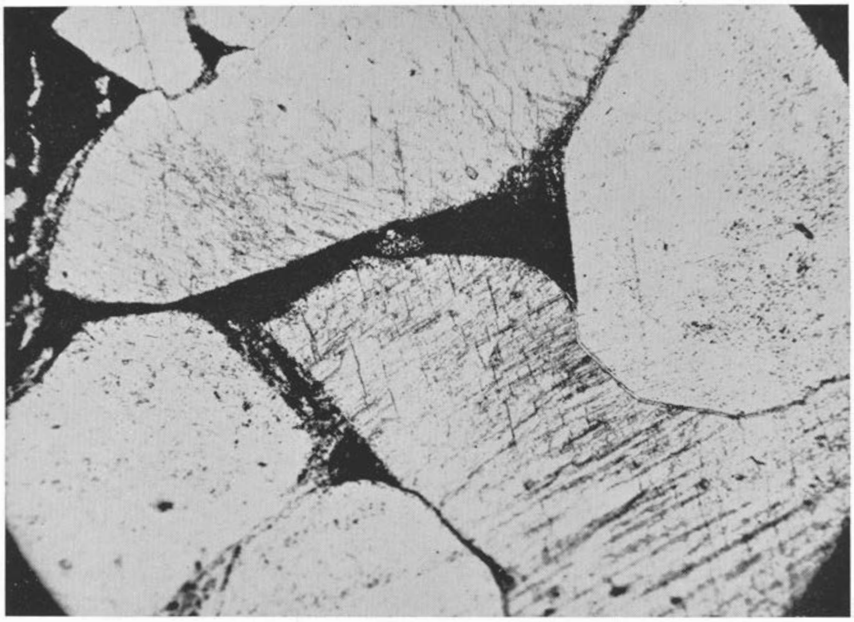

Fig. 30. Crystalline-granular texture. Matrix bituminous. Anthraconite. Lower Ordovician. Knivinge, Östergötland. (Prep. 7776, photo 1579.) — 60×.

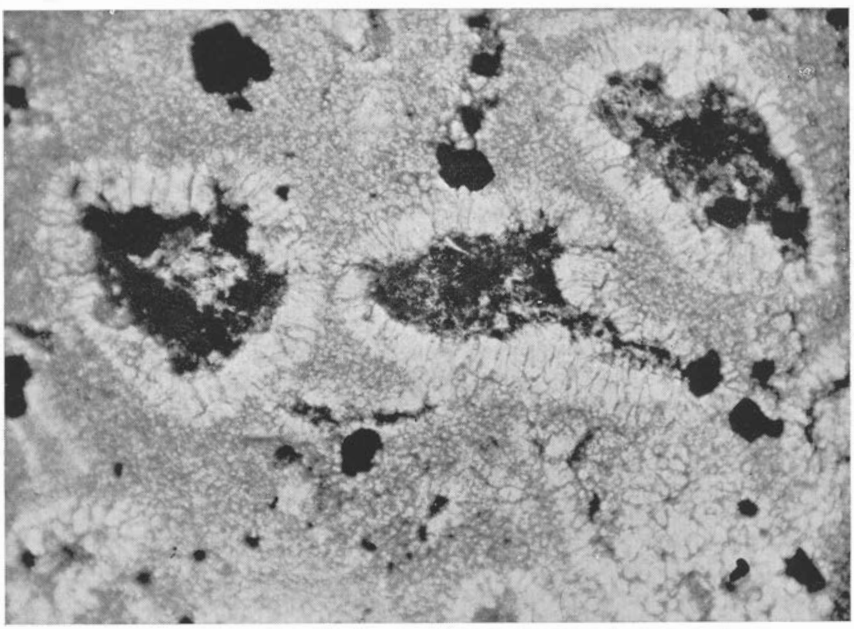

Fig. 31. Crystalline-granular texture. Bitumen pockets with crust of radiated calcite crystals. Ceratopyge limestone. Flagabro, Skåne. (Prep. 6318, photo 1299.) — 60×.

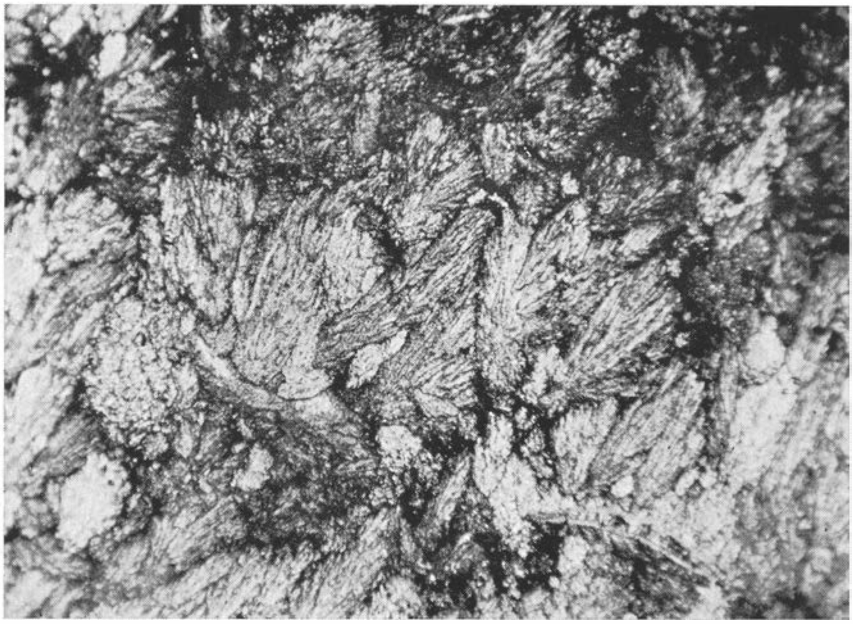

Fig. 32. Fibrous texture. Bituminous Andrarum limestone. Middle Ordovician. Andrarum, Skåne. (Prep. 6561, photo 1749.) — 20×.

Fig. 33. Lenticular texture. Chasmops limestone, Middle Ordovician. Tandsbyn, Jämtland.

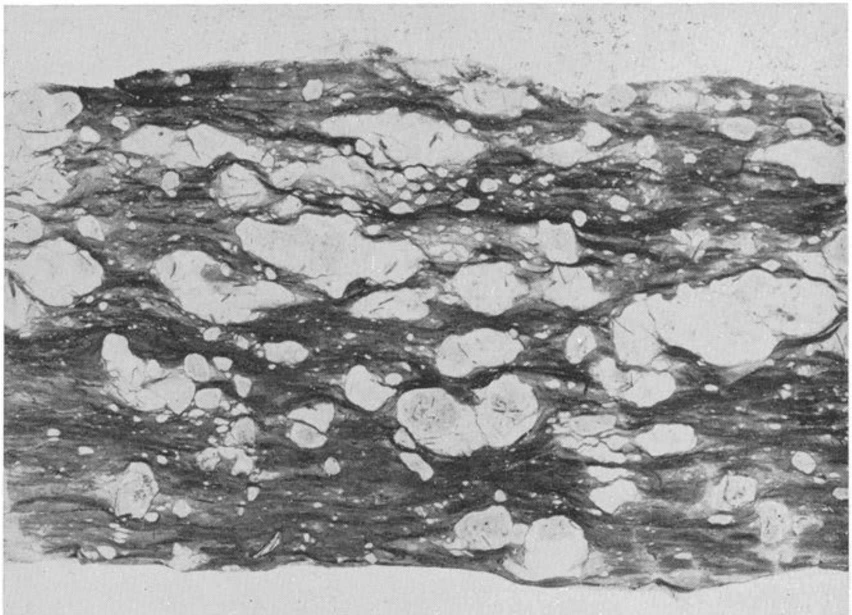

Fig. 34. Knobby texture. Middle Ordovician limestone, Öglunda, Västergötland. (Photo 1509.) — $^1/_1$.

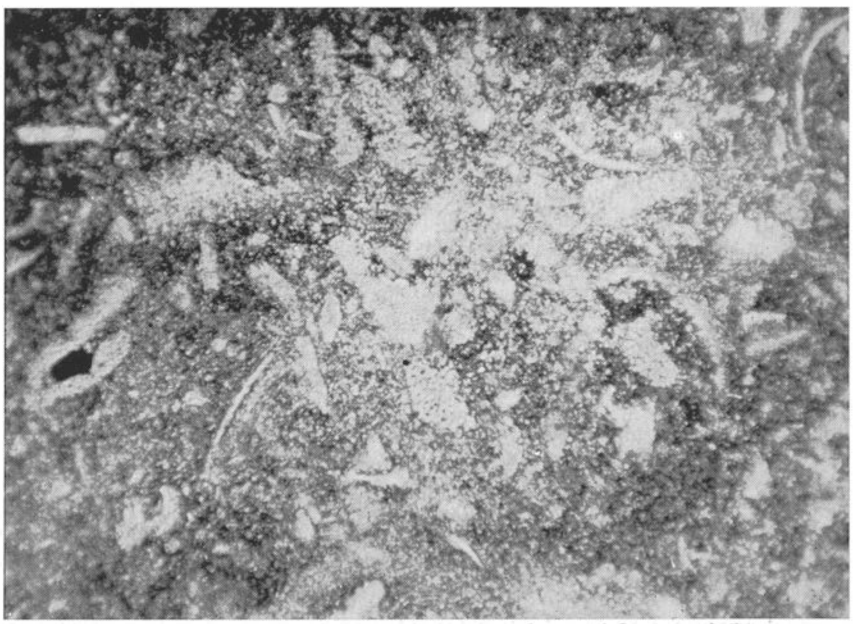

Fig. 35. Fragment limestone with strongly corroded fossils. Orthoceras limestone. Fågelsång, Skåne. (Prep. 6585, photo 1319.) — 60 ×.

Fig. 36. Microcrystalline fragment limestone with large trilobite carapaces. Exsulans limestone, Middle Cambrian. Brantevik, Skåne. (Prep. 7820, photo 1739.) — 20×.

distinct traces of dissolution or corrosion (fig. 35). But generally there is reason to assume that this effect occurred before or in connection with deposition and embedding.

The effect of diagenesis on fossils is often very appreciable, and not infrequently it is possible through a study of the fossils to acquire a clear picture of the effect of diagenesis on the sediment, too. Certain fossils have primarily a crystalline structure so constituted that any possible diagenetic changes are scarcely noticeable. This is the case with pelmatozoans. Others are transformed even by slight diagenesis, e. g. some corals and hydrocorals. Trilobite fragments and brachiopod shells together with calcareous algae, on the other hand, show great powers of resistance under diagenetic influences (fig. 36).

The diagenetic change of fossils is principally a recrystallization of the calcareous matter. The texture may be retained in its coarse features, and the external shape and sculpture may be completely unchanged. Under increased diagenetic action the organic texture is more and more obliterated, and the external shape, too, may undergo changes. Shells become thinner and thinner, and then they are often surrounded by a new-formed crust of radiated calcite (fig. 36). Finally the fossil may be completely obliterated by diagenetic recrystallization. Radiated calcite formed around the fossil may sometimes remain as evidence of the former existence of the fossil.

SELECTED EXAMPLES OF SWEDISH CAMBRIAN AND ORDOVICIAN LIMESTONES.

The limestones to be discussed below with regard to character and formation are intended to be a representative collection of the Cambrian and Ordovician calcareous sediments of Sweden. The macroscopic and microscopic nature, texture, and composition of the rocks have been dealt with summarily and schematically, which is justified by the fact that references are made to illustrative photographs.

It would have been desirable for the description not to be restricted to individual beds or samples of them. The author has in many cases followed the beds throughout whole series of strata and studied the changes in sedimentation. He wishes that it had been possible to illustrate all the more essential variations which the series display. But it would have taken up far too much space. In the summarizing survey which the author plans to make in a projected continuation of this study, he hopes to be able to take up some of the problems which must be passed over here. They can be more comprehensively elucidated when an account has also been given of studies of the Silurian and Cretaceous deposits of Sweden.

Notes on pre-Cambrian limestones.

The limestones of the Archean are greatly metamorphosed. They occur together with other deformed sediments as quartzites, slates, mica schists, sedimentary gneisses, and iron ores. Several of these oldest limestones are of considerable thickness and extension. Their primary character, stratification, and relative age can only be determined to a degree, and an attempt to interpret their different conditions of formation would be a difficult (though undeniably attractive) task. A couple of examples of the Archean limestones will be given here.

Limestone at Ställberg mines.

The limestone belongs to the Leptite formation, Sweden's oldest Archean rocks. Like the other rocks in this formation the limestone is greatly metamorphosed, and nothing of its primary texture is preserved. Besides calcite the rock contains calcium silicates. A condition of interest from a lithological point of view is the fact that the

Fig. 37. Archean limestone with folded schists. Kalkholmen, Stockholm archipelago.

rocks occur in stratigraphical horizons which are undoubtedly primary. At the Ställberg mines one can follow the various layers for a distance of several hundred metres (Geijer and Magnusson 1944, pl. 21). The individual limestone beds are unusually persistent, and they occur regularly in the partially pyroclastic leptites. One might have expected greater variations, less continuity, and above all, greater disturbances in the series of strata as a result of the extensive regional metamorphism.

Limestone in the banded series of the Stockholm archipelago.

The limestone belongs to Sweden's older Archean rocks. It is greatly metamorphosed, completely crystalline-granular, and rich in new-formed minerals, especially calcium silicates such as diopside, tremolite, scapolite, etc. (Sundius 1939). The way in which the limestone occurs interstratified in and alternating with leptite shows that in this area, as in the above-mentioned Ställberg field, it occurs in its primary stratigraphic position. The series of strata has, however, been greatly disturbed (fig. 37).

The two limestones mentioned above, like so many others of similar character, are of great importance for a general understanding of the sediment formation of the older Archean. Unfortunately, they do not show how the calcium carbonate was precipitated primarily: whether it occured inorganically or with the assistance of organisms.

There is a striking difference between the sediments of Sweden's older Archean and those of the younger pre-Cambrian series of strata. The younger Archean and the Algonkian sediments consist of conglomerates, sandstones, and shales, more or less metamorphosed to quartzites, mica schists, and gneisses. Limestones and sedimentary iron ores, which form such a prominent feature of the older Archean, are almost completely absent in the younger pre-Cambrian series of strata.[1] Differentiation of the weathering matter, however, has been similar throughout, if we disregard the variations in the weathering itself, which can be as easily observed in pre-Cambrian sediments as in younger sediments. The different development of the sediment series of the older and younger pre-Cambrian has been caused by differences in their environments of formation. The not very calcareous or ferruginous sediment series of the younger Archean are of a typical continental nature, and their environments of formation have not been favourable for large accumulations of calcareous and ferruginous sediments. There is good reason for suspecting that the series of strata rich in limestones and iron ores which was formed during the older Archean, is a marine deposit. The small boron-content, 0,001 % or less, of certain older Archean iron ores does not, however, indicate marine origin. In younger, marine iron ores the B-content is around 0,005 %, often greater. (Cf. LANDERGREN 1948, p. 110 ff.) For a large part of the calcareous and siliceous ores LANDERGREN gives the B_2O_3-contents as 0,006—0,030 %, and for manganese-bearing iron ores even higher percentages. Other sediments of the limestone-bearing Archean series of strata have a relatively high boron-content.

Cambrian limestones.

The paleozoic sediments of Northern Sweden are mostly deformed, folded, and overthrust. Relatively undisturbed sections are, however, seen east of the thrusts. The Paleozoic of Middle and Southern Sweden is better preserved, partly quite undisturbed and unaltered.

The Lower and Upper Cambrian sediments are more complete in Skåne than in other parts of Sweden. The Middle Cambrian is relatively uniformly developed. The varying types of limestone will be discussed by means of selected examples.

Calcareous sediments of the Lower and Middle Cambrian.

The marine Lower Cambrian series of strata in Sweden consists chiefly of sandstones, formed in the littoral belt. Arkoses and conglomerates occur in the basal deposits, grey shales higher up in the series. Glauconitic and phosporitic beds are found in certain areas. Calcareous sediments occur in the upper part of the Lower

[1] Limestones and calcareous sandstones occur but only in small quantities and very impure (e.g. the Hede limestone of the Sparagmite formation. See HADDING 1929, p. 158).

Cambrian, mainly in the form of calcareous sandstones; only in a few places do they grade over into more or less arenaceous limestone beds. Here will be mentioned some of the rocks in Skåne and at Torneträsk in Lapland. The Middle Cambrian limestones are found in several places in different parts of the series of strata.

Lower Cambrian limestones at Torneträsk, Lapland.

The Lower Cambrian limestone on Luopahta at Torneträsk (lat. 68° 45′ N) occurs in two separate horizons: the upper, a fragmental limestone, at the boundary with the Middle Cambrian; the lower, a dense limestone, at a level 17 m lower. The latter limestone is the oldest in the marine Cambrian series of strata in Scandinavia. Both belong, however, to the upper zone of the Lower Cambrian, the Kjerulfi stage.

The lower limestone on Luopahta.

Macro: Dark-grey, dense, in parts spathic limestone with glistering small grains of quartz and scattered, somewhat larger, dull, dark grains. The weathering-crust is rust-coloured and porous.

Micro: The limestone is completely recrystallized, but the calcite aggregates or the crystals are separated by a matrix of argillaceous and organic matter. The calcite grains vary in size: in certain portions they are only 15 μ, in others 50 or 100 μ. Broom- or plume-like calcite aggregates may penetrate the matrix from the more coarse-crystalline parts (fig. 38). The texture is then reminiscent of that found in anthraconite. — Fossils are extremely rare. Grains of quartz occur abundantly in certain layers, sparsely in others. In the former case well rounded, 2—3 mm-large grains occur together with the small splinters found scattered throughout the rock. The dark grains, which can be seen with the naked eye, are brown in transmitted light, sometimes dark, sometimes faintly coloured. They do not show any double refraction. Some are uniformly coloured without marks; others, particularly the darkest ones, have an irregular, concentric texture, outgrowth zones or rhythmically precipitated pigment. The structure recalls certain calcareous algae. A few grains are of the same shape as cracked glauconite grains; others are of the same colour and density as the phosphorite found in several Lower Cambrian sandstones.

Diagenesis: The lower grey limestone at Torneträsk has been recrystallized during diagenesis without its primary character being obliterated.

Formation: The limestone has been formed as calcareous mud with arenaceous layers. The limestone overlies a dark (carbonaceous) sandstone and is covered by an arenaceous shale. The nature of the limestone and its appearance in the series of strata show that it has been formed outside the littoral zone, at little depth, and in fairly quiet water. The fossil fragments (trilobites) indicate its marine character.

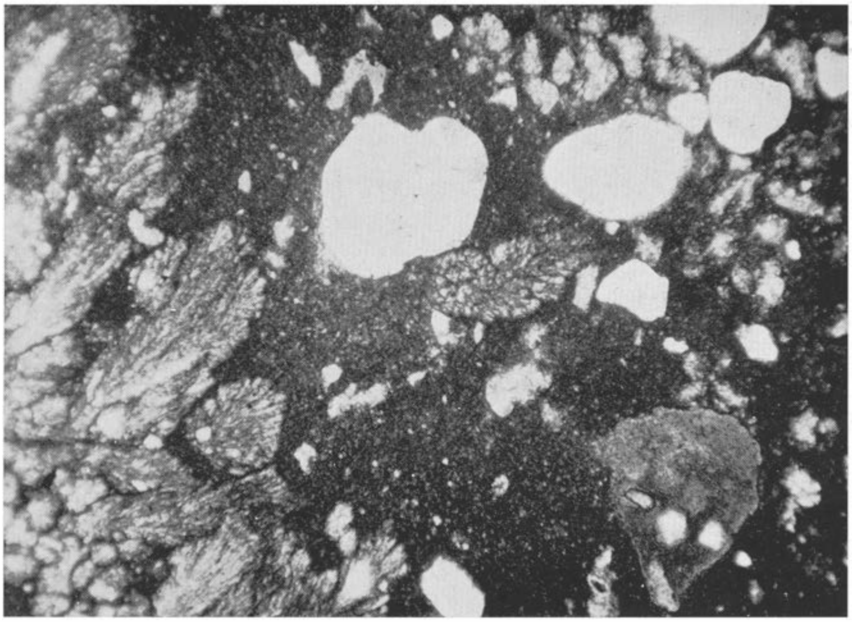

Fig. 38. Limestone with fibrous calcite crystals and quartz in argillaceous-bituminous matrix. Lower Cambrian. Luopahta, Lappland. (Prep. 2843, photo 1736.) — 20 ×.

The upper limestone on Luopahta.

Macro: Dense, black or dark-grey limestone with irregular splintery fracture. Traces of dissolved fossils are visible on the weathering-surface.

Micro: Even-grained, microcrystalline calcite mass with irregularly distributed dark pigment. Small, irregularly shaped pyrite aggregates and fibrous, carbonaceous fragments are scattered throughout the rock. Small, angular grains of quartz (20—200 μ) occur abundantly in certain portions. The limestone consists largely of fossil fragments (trilobites), 0.5—1 mm, completely recrystallized (fig. 39).

Formation: The rock is a typical fragment limestone, formed through accumulation of fragments which were primarily embedded in mud. The limestone has been formed during a change of activity of the water. As the change occurred contemporaneously in northernmost and southernmost Sweden, we have reason to interpret it as a consequence of land elevation. This has not left the same traces everywhere. In certain places we find it as a break in the series of strata, in others as a unique shallow-water sediment, e. g. glauconitic shale (Andrarum and Gislövshammar in Skåne, Bornholm).

The Lower and Middle Cambrian limestones of Skåne.

Nowhere in Sweden is the Cambrian series of strata so complete and so well preserved as in Skåne. In the Lower Cambrian it is composed principally of sand-

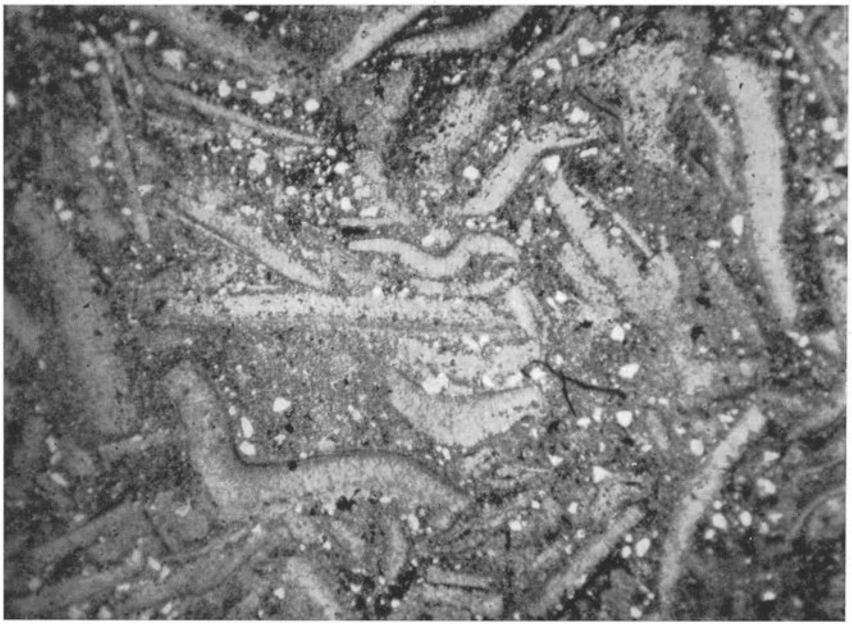

Fig. 39. Arenaceous fragment limestone. Lower Cambrian. Luopahta, Lappland. (Prep. 7511, photo 1743.) — 20×.

stones, in the Upper Cambrian of alum shales. Limestones only occur sparsely, mainly in the form of anthraconites or bituminous fragment limestones, which appear together with alum shale, as the adjoining table shows.

Upper Cambrian	Olenus series	Alum shales with anthraconites
Middle Cambrian	Paradoxides forchhammeri stage	Alum shale Andrarum limestone Hyolithes limestone Alum shale
	Paradoxides paradoxissimus stage	Alum shale Exsulans limestone Alum shale
	Paradoxides oelandicus[1] stage?	Phosphorite limestone Grey shale
Lower Cambrian	Holmia kjerulfi stage	Arenaceous limestone Grey shale
	Schmidtiellus torelli stage (Hardeberga sandstone)	Calcareous sandstone with phosphorite Quartzitic sandstones

[1] The rocks which are here doubtfully reckoned with the *Paradoxides oelandicus* stage are

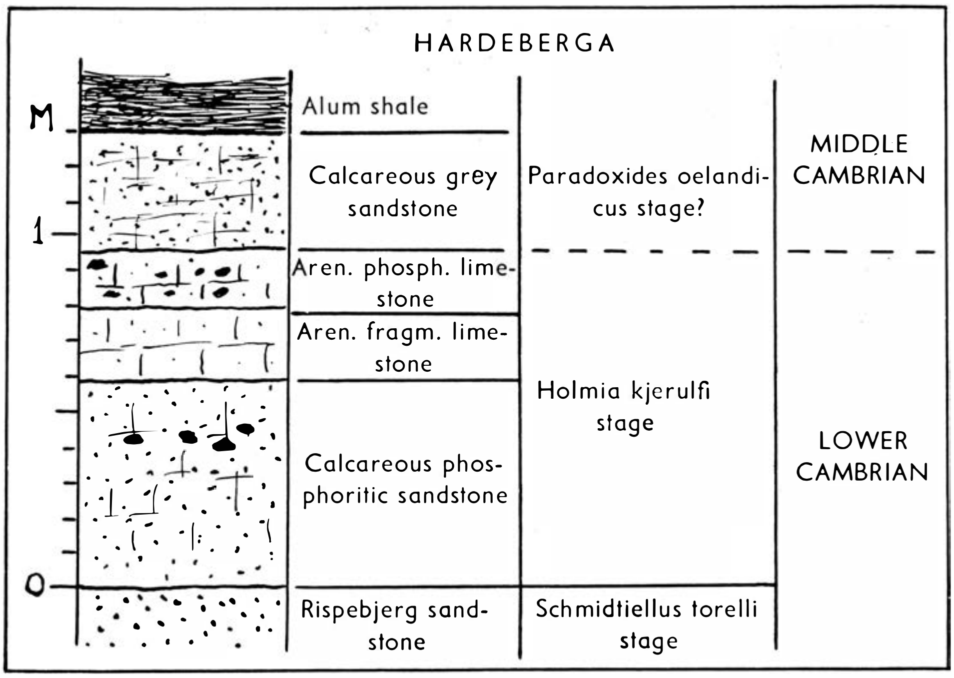

Fig. 40. Section through the Lower and Middle Cambrian beds at Hardeberga, Skåne.

More detailed sections of various parts of the Cambrian series of strata are given in figs. 40, 43, and 47.

The Lower Cambrian limestone at Hardeberga.

The Lower Cambrian sandstone at Hardeberga in Skåne is covered by a highly calcareous series with fossils belonging to the stages with *Holmia kjerulfi* and *Paradoxides oelandicus* (see section fig. 40).[1] Certain parts of this series must be considered as calcareous sandstone; others, in spite of grains of quartz, as limestone. It is difficult, however, to draw the boundaries between them, for which reason the rocks and their thickness have been differently appraised. Below a report is given on the rocks which Troedsson (1917, p. 627) called fragment limestone and phosphoritic limestone, the latter below and in the section fig. 40 designated arenaceous, phosphoritic limestone.

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divided by several investigators between the *Paradoxides paradoxissimus* stage (Middle Cambrian) and the *Holmia kjerulfi* stage (Lower Cambrian). Cf. following pages.

[1] The characteristic bed of arenaceous, glauconitic limestone (with phosphorite) which occurs in several places, e.g. at Andrarum, Brantevik, and Hardeberga, has been regarded as the youngest part of the *Holmia kjerulfi* stage. The younger layers have been regarded as belonging to the stage with *Paradoxides oelandicus*. This stage is generally considered to be absent in Skåne (see e.g. Westergård 1946, p. 9).

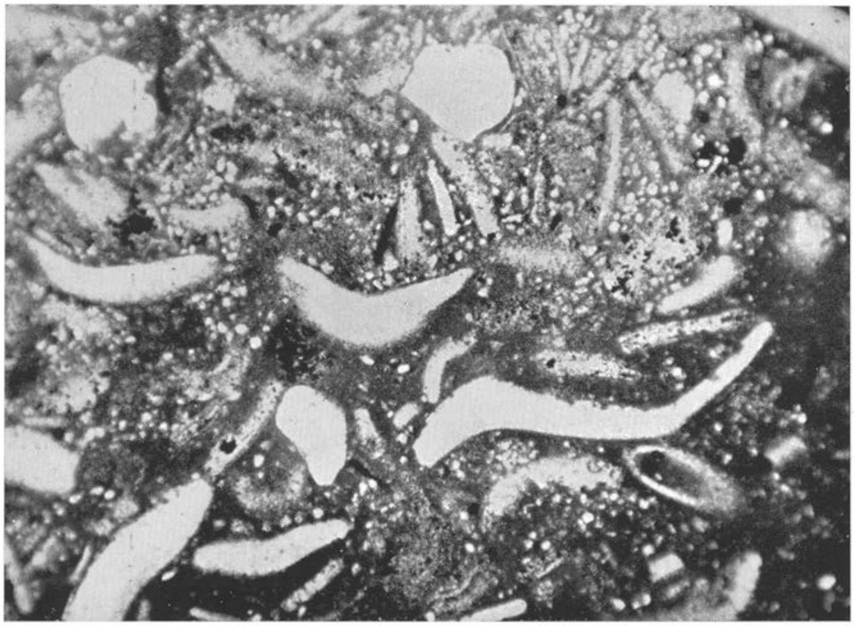

Fig. 41. Arenaceous fragment limestone. Lower Cambrian. Hardeberga. Skåne. (Prep. 2783, photo 1729.) — 20×.

The arenaceous fragment limestone, Hardeberga.

Macro: The limestone is light-grey and granular in the lower part, but dark-grey, bituminous, and dense in the upper part, with a well defined boundary with the overlying phosphoritic limestone, with which it forms a continuous bed.

Micro: The ground-mass is even-grained, microcrystalline with calcite grains about 10 μ. Fragments of brachiopods and trilobites, 1—5 mm, occupy approx. 30 % of the mass (fig. 41). They are greatly recrystallized but with the contours clearly preserved. In certain parts they are impregnated with pyrite. Small quartz fragments, 15—16 μ, occur fairly abundantly; larger rounded grains of quartz, 0,5—1 mm, only exceptionally. Pyrite occurs in crystals and small aggregates, 5—15 μ (see fig. 13, p. 28), but not phosphorite or glauconite.

The arenaceous, phosphoritic limestone, Hardeberga.

Macro: The upper part of the bed is light, granular or spathic, with a well defined boundary with the underlying dark fragment limestone. Dense, black phosphatic nodules occur generally. In some cases they reach a size of approx. 10 mm, but the majority are only 1 mm or less. There are abundant small grains of quartz, 0,05—0,2 mm, in the spathic calcite aggregate.

Micro: No calcareous fragments are found preserved, and phosphatic shells

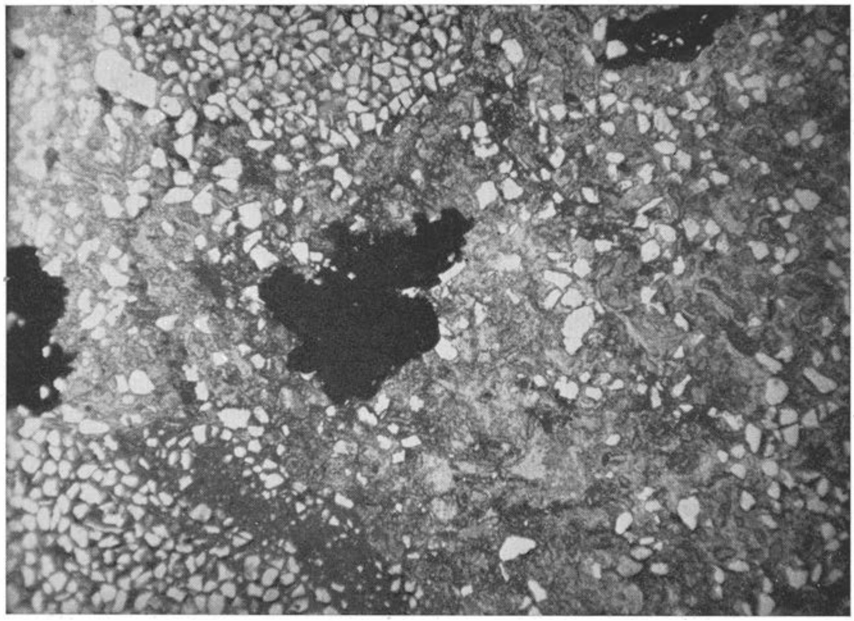

Fig. 42. Arenaceous, phosphoritic limestone. Lower left: phosphatic nodule filled with quartz. Black parts pyrite. Lower Cambrian. Hardeberga, Skåne. (Prep. 8763, photo 1782.) — 20 ×.

occur only scantily. The phosphatic nodules are partly authigenic, partly allotigenic. The latter have been formed in an environment with more finely arenaceous sedimentation (fig. 42). Certain of the phosphatic nodules also contain glauconite, in exceptional cases as unweathered green grains, usually as changed, yellow. The latter type of glauconite grains also occurs abundantly in the matrix of the rock but not in the underlying fragment limestone. Pyrite in aggregates and as impregnation in the phosphorite.

The two limestones discussed above form, as has already been mentioned, a solid bed, but the boundary between them is sharply marked by the difference in colour. The boundary also marks a definite change in the sedimentation. The appearance of authigenic phosphorite and phosphatic nodules, abundant glauconite, somewhat increased size of the quartz fragments, and decrease in the bitumen-content characterize the arenaceous, phosphoritic and glauconitic limestone and clearly distinguish it from the underlying fragment limestone. Increased turbulence of the water prevented deposition of the dark, highly bituminous mud which forms part of the fragment limestone. Probably the already formed uppermost mud layer was washed away, whereupon deposition of the phosphoritic limestone took place. The change in the sedimentation conditions resulted in accumulation of fossil fragments, primarily deposited in the same way as those found in the fragment limestone. That no calcareous fossils can be shown to exist is due to the fact that the limestone has recrystallized during diagenesis and been converted to a coarsely spathic calcite aggregate.

The arenaceous, phosphoritic, and glauconitic limestone at Hardeberga partly fills the gap in the series of strata which is found between the stage with *Holmia kjerulfi* and the stage with *Paradoxides paradoxissimus*. The gap together with the phosphoritic limestone may represent the stage with *Paradoxides oelandicus*, which has not been shown by fossil finds to exist in Skåne.[1]

The Lower and Middle Cambrian limestones of S. E. Skåne.

The series of strata at Andrarum was published by NATHORST (1869 and 1877), and it has since been mentioned by various writers, e. g. TULLBERG (1880, p. 3 and 1882, p. 13), LINNARSSON (1882), MOBERG (1910, p. 59 ff.), GRÖNWALL (1902, pp. 172 and 179, and 1916, p. 63). Designation of the various layers has varied, as also the drawing of the boundaries between them. The section published here, fig. 43, was measured in 1939 by a member of a course in field geology, when, however, only the lower part of the Exsulans limestone was accessible. WESTERGÅRD (1944, p. 28) gave details of a drill-core from Andrarum, in which the Lower Cambrian strata are also included, but unfortunately in incomplete form.

Arenaceous, glauconitic-phosphoritic limestone, Andrarum.

The Lower Cambrian series of strata at Andrarum in south-east Skåne contains several sandstones with calcite cement. The formation of this calcium carbonate has occurred in the same way as in corresponding rocks at Hardeberga and other places. The sandstones are overlain by grey, arenaceous shale (Greywacke shale) with the characteristic fossils of the Kjerulfi stage. In the upper part of this series of shales is a very glauconitic, calcareous sandstone or arenaceous limestone with profuse fossil fragments. The rock also contains phosphatic nodules and has therefore generally been called phosphoritic limestone. With better cause it ought to be called glauconitic limestone or glauconitic, arenaceous limestone.

Macro: Bed 9 cm thick. Macroscopically the rock is coarse-crystalline and fine-grained, almost dense, hard, partly silicified, and with splintery fracture. The colour is dark greenish-grey with dark-brown slices and brown lumps (phosphorite). Dully shining planes of cleavage are seen in large calcite crystals. (Rock specimen 4816.)

[1] If determinable fossils are found in the phosphorite-glauconite limestone, e.g. phosphatic shells of brachiopods, they may just as likely originate from otherwise washed-away mud deposited during Kjerulfi time as from Oelandicus or Paradoxissimus time. TROEDSSON states that he has found fragments of *Acrothele bellapuntata* WALC. and *Acrotreta sagittalis* SALT. in the phosphoritic limestone. TROEDSSON himself reckons the phosphoritic limestone with the Lower Cambrian (Kjerulfi zone). Cf. WESTERGÅRD 1929, p. 14, note 6. The phosphoritic limestone is a direct equivalent of the arenaceous, glauconitic-phosphoritic limestone in the uppermost part of the Kjerulfi stage at Forsemölla, Andrarum.

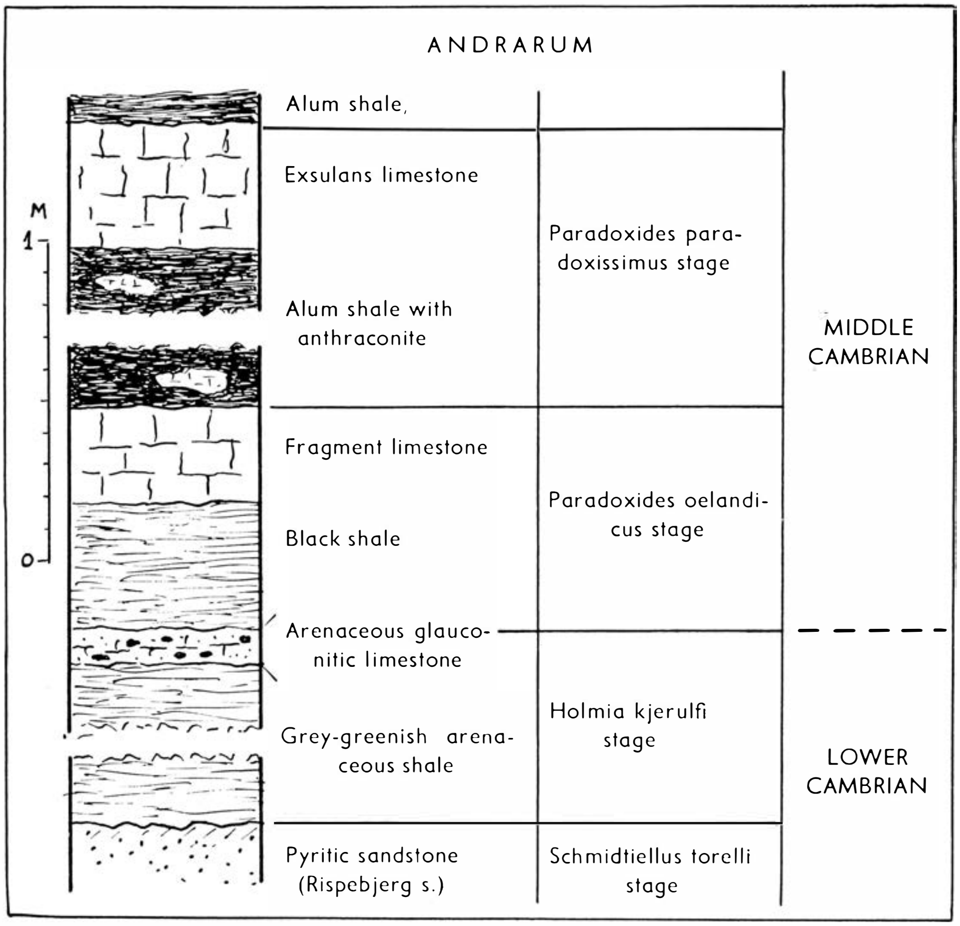

Fig. 43. Section through the Lower and Middle Cambrian beds at Andrarum, Skåne.

Micro: The rock consists of calcite crystals (3—10 mm), packed with sharply angular grains of quartz (50—100 μ) and irregular, lobate, light-green glauconite which together take up more than 50 % of the whole mass (fig. 44). In this green part there are also brown shell fragments and phosphorite lumps (0,5—3 mm). The glauconite grains are of the same size as the quartz grains (0,05—0,1 mm), and one might possibly from that be misled into certain conclusions concerning the conditions of sedimentation. A closer examination reveals, however, that the small lobate grains of glauconite now found in the rock are only the core-portions of primarily larger, rounded grains of glauconite, which in the peripheral part have been replaced by calcite through metasomatism. The transformation, which is not unique, together with the cementation, has resulted in the original quartz-glauconite sand being changed to an arenaceous glauconitic limestone. The glauconite grains primarily had a diameter of 0,2—0,4 mm.

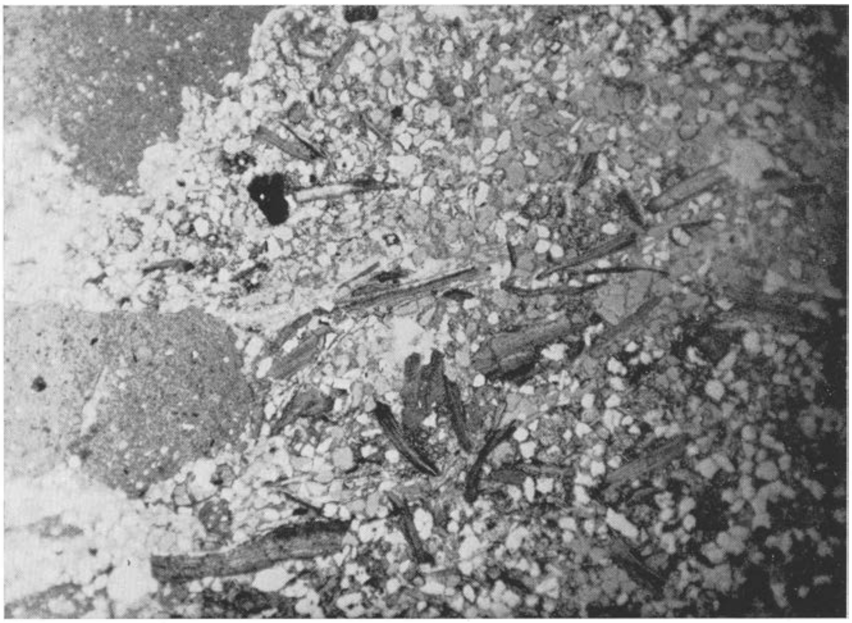

Fig. 44. Arenaceous limestone with phosphorite nodules (left), glauconite grains and phosphatic shell fragments. Lower Cambrian. Andrarum, Skåne. (Prep. 8758, photo 1720.) — 20 ×.

The brown shell fragments consist of phosphate. The grains and lumps of phosphorite, which contain grains of quartz, not more than 40 μ in diameter, have chiefly been formed in a different environment from that in which they are now found (cf. HADDING 1932, p. 107). Pyrite in small crystals.

Certain parts of the bed consist entirely of phosphorite lumps and phosphatic shells in a granular matrix of glauconite and grains of quartz. Here and there this only slightly calcareous part of the bed is silicified with fibrous chalcedony.

Diagenesis: The diagenetic transformation has principally been new-formation of calcite and chalcedony. (The underlying layers show strong silicification.)

Formation: The glauconitic limestone at Andrarum has been deposited primarily as quartz-glauconite sand with intermingled fragments of phosphatic shells and phosphorite lumps. Formation has taken place in turbulent water, where grains of quartz and secondarily occurring glauconite and phosphorite have been accumulated. The absence of pyrite and bitumen indicate also fairly mud-free, open water. The origin of the calcium carbonate is not clear from the data concerning the nature of the rock which it was possible to give above. The immediately overlying stratum is composed of black shale without any appreciable content of calcium carbonate, and we must therefore rather assume that the quartz-glauconite sand primarily contained fragments of calcium-carbonate-forming organisms, too. Calcareous fossils play a dominating role in the nearest younger limestone. It is improbable, however, that the calcium carbonate in the lower bed can originate from there.

The age of the quartzitic, glauconitic limestone discussed above has not been established. The bed below, the Greywacke shale, belongs to the Lower Cambrian (Kjerulfi stage); that above, the black shale, belongs to the centralmost part of the Middle Cambrian (Paradoxissimus stage). The high content of quartz and glauconite in the limestone shows its kinship with the corresponding layer of the drilling at Gislövshammar, a glauconitic sandstone (WESTERGÅRD 1944, p. 29).[1] The arenaceous glauconite-phosphorite limestone at Andrarum lies on the boundary between the Lower and Middle Cambrian and represents the uppermost part of the Kjerulfi stage or the lowermost part of the Oelandicus stage. The latter zone has a thickness of nearly 60 m in Öland but is almost non-existent in Skåne and on Bornholm (cf. WESTERGÅRD 1944, p. 26).

Fragment limestone, Andrarum.

Macro: The oldest limestone of the Middle Cambrian series of strata in Skåne has generally been called fragment limestone, and it gives cause for its name. Macroscopically the rock is light in certain portions, dark or flamy in others.

Micro: The limestone consists of accumulated fragments, 0,5—3 mm long, mostly of exoskeletons of trilobites (fig. 45). A few phosphatic shells (*Lingula*, *Acrotreta*) lie scattered among the fragments. Small phosphorite balls (coprolites) occur sparingly. The matrix is always primarily calcareous mud. During diagenesis it has sometimes been partly replaced by barytes. Grains of quartz, 0,05—0,15 mm, are found scattered in certain parts of the limestone, usually together with small grains of glauconite. Pyrite is generally present in small aggregates or cubes.

Formation: The formation of the fragment limestone took place in several stages. Accumulation of calcareous fragments in enormous masses requires rich development of organisms (trilobites). The animals must have lived in an environment with abundant nutriment, not in a fragment-filled calcareous mass of which the rock is built up. The first stage in the formation of limestone was in this case the development of trilobites in an environment favourable to them, presumably an argillaceous, organic mud. The next stage of formation of the rock was disintegration of the carapaces and accumulation of the fragments. How the breaking-up occurred, whether by means of organisms or purely mechanically, is not apparent from their appearance or that of the rock. Accumulation occurred by means of transportation, separation, and deposition in moderately turbulent water, which did not permit sedimentation of whole mud layers. The fragments were deposited on top of and largely parallel to one another. This parallel structure, however, has been obliterated during the third stage of formation of the limestone. This comprises a sliding of the sediment. During this the carapaces were wrenched from the horizontal position, and

[1] A comparison of these beds with the uppermost part of the green shales ("Grönne Skifere") of Bornholm is not justified, however. These Lower Cambrian glauconitic shales of Bornholm are of the same age as those at Brantevik (Torelli stage) (cf. HADDING 1929, p. 98).

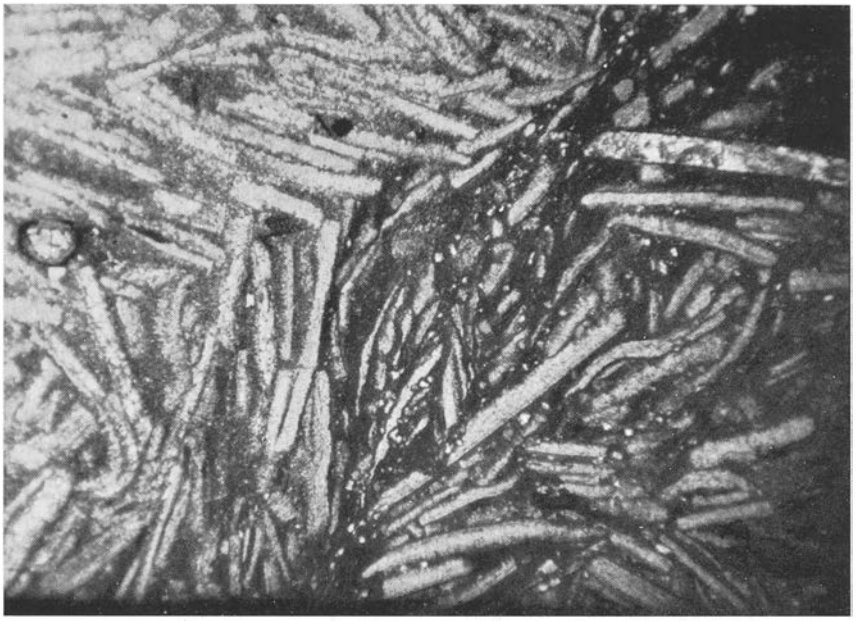

Fig. 45. Fragment limestone. Slid sediment. Middle Cambrian. Andrarum, Skåne. (Prep. 7331, photo 1721.) — 20×.

Fig. 46. Barytes in fragment limestone. Middle Cambrian. Andrarum, Skåne. (Prep. 3063, photo 1723.) — 20×.

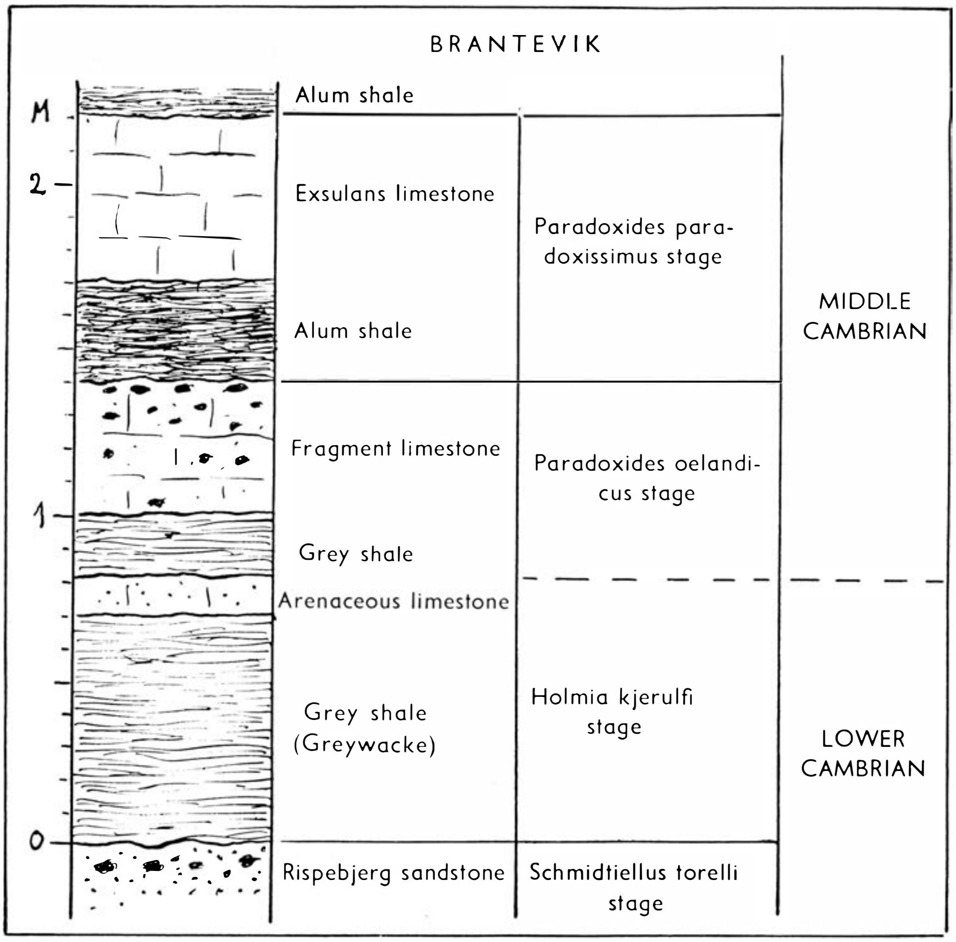

Fig. 47. Section through the Lower and Middle Cambrian beds at Brantevik, Skåne.

they now lie unoriented in the rock. The fourth stage, diagenesis, comprises crystallization of the matrix (calcite mud). In certain parts of the rock metasomatism followed, the calcite being replaced by baryte.

The barytes occurs as irregular, skeletal crystals, intermingled with the fragments, sometimes sparsely, sometimes more profusely (fig. 46).[1]

Arenaceous limestone, Brantevik.

In the shore section between Brantevik and Gislövshammar the coarse-grained, white phosphoritic sandstone (Rispebjerg sandstone) is overlain by Greywacke

[1] The baryte displays characteristic cleavages. The approximate values obtained in optical examination were: n = 1,6. Optically negative. Straight extinguishing. 2 V = 38°, $\gamma - \alpha = 0{,}011 \pm \pm 0{,}002$.

Fig. 48. Arenaceous limestone. Holmia kjerulfi stage. Lower Cambrian. Between Brantevik and Gislövshammar, Skåne. (Prep. 8766, photo 1728.) — 20×.

shale (see section fig. 47). In this shale lies a thin limestone bed in which have been encountered *Hyolithellus* and *Strenuella* together with other fossils belonging to the stage with *Holmia kjerulfi*.[1]

Macro: The limestone is faintly greenish-grey, dense but with profuse fragments, best visible on weathered surface. Glauconite has been observed as a thin coating on a few larger fragments and as occasional diffuse flocks or impregnations in the calcite ground-mass. Phosphorite cannot be observed with the naked eye. Pyrite occurs in scattered small grains.

Micro: The calcite ground-mass is fine-crystalline (grains 10—30 μ). There is no bitumen. Quartz occurs in angular grains, 30—50 μ, fairly generally scattered in the ground-mass (fig. 48). Small brown isotropic, angular or irregular grains and flocks, 50—100 μ, lie squeezed in between the calcite grains. They are interpreted by the author as authigenic phosphorite. Phosphatic shells are found in small quantity, generally much corroded. The fragments of trilobites are well preserved, 0,5—6 mm or

[1] The shale together with the limestone forms the uppermost part of the Lower Cambrian and is a direct equivalent of the Greywacke shale at Andrarum, as also of the Greywacke shale found in the drilling at Gislövshammar. In all these places the shale and the limestone with *Holmia kjerulfi* are overlain by glauconitic, arenaceous limestone or sandstone, in turn overlain by fragment limestone with phosphorite, which in Skåne has been regarded either as the basal stratum of the stage with *Paradoxides paradoxissimus* or as the upper part of the stage with *Paradoxides oelandicus*. Cf. Westergård 1929, p. 14.

more. They occupy less than 20 % of the rock. Glauconite has been observed in occasional small grains (10 μ).

Diagenesis: Ground-mass and fragments completely recrystallized.

Formation: The limestone with *Hyolithellus* has been formed during a temporary increase in (organic?) calcite production during the phase which is otherwise characterized by arenaceous and argillaceous deposits. Deposition occurred in shallow, slightly turbulent water and neutral environment.

Fragment limestone with glauconite and phosphorite, Brantevik.

The fragment limestone at Andrarum has a direct equivalent on the south-east coast of Skåne in a phosphoritic, glauconitic fragment limestone at Brantevik. The rock crops out on the beach 1 km south of the harbour. The sequence of strata is apparent from the section in fig. 47.

Macro: The fragment limestone at Brantevik is different in certain respects from that at Andrarum. Macroscopically the rock is dark-grey with light-grey weathering-crust. It contains numerous dense, black phosphatic nodules and on the upper surface of the bed large lumps of phosphorite. Small dark-green grains of glauconite, pyrite aggregates, and fossil fragments are visible on the weathering-surfaces.

Micro: The rock consists for about 50 % of worn trilobite fragments, 0,3—3 mm long (fig. 49). In the microcrystalline ground-mass (matrix) the calcite crystals ($<$10 μ) are separated by dark, organic pigment. The phosphatic nodules are brown and isotropic in transmitted light. Some of them contain only grains of quartz, others quartz and glauconite, the latter mineral in irregularly lobate aggregates, 20—60 μ. Phosphatic nodules without foreign inclusions but with phosphatic shells are also found.

The glauconite grains of the ground-mass are rounded, fairly large ($>$200 μ), clear green but occasionally entirely or partly dark-pigmented. The glauconite grains have often been replaced peripherally by secondarily formed calcite crystals.

Barytes occurs in small quantity as irregular aggregates, 0,2—2 mm large (fig. 50). The cleavage-planes appear even macroscopically in the fine-grained ground-mass.

Diagenesis: Diagenesis has had a different effect in different parts of the rock. The matrix, however, is always completely crystalline, the clastic texture is well preserved, however.

Formation: The fragment limestone at Brantevik has been formed in stages, in the same way as the corresponding rock at Andrarum, but the environment of formation has lent it an individual character. The high content of allotigenic phosphorite in larger and smaller nodules together with the occurrence of abundant glauconite grains shows that sedimentation took place in more turbulent water at Brantevik than at Andrarum. This is supported by the fact that the alum shale between the fragment limestone and the Exsulans limestone has a thickness of only 1,2 m at Brantevik against 4 m at Andrarum.

Fig. 49. Fragment limestone with glauconite grains. Slid sediment. Middle Cambrian. Brantevik, Skåne. (Prep. 7789, photo 1741). — 20×.

Fig. 50. Barytes (white), pyrite, and calcite (grey) in microcrystalline matrix. Fragment limestone. Middle Cambrian. Brantevik, Skåne. (Prep. 7787, photo 1740.) — 20×.

Fragment limestone with phosphorite, Kiviks Esperöd.

At Kiviks Esperöd on the east coast of Skåne, 16 km east of Andrarum and 20 km north of Brantevik, was found a fragment limestone with phosphorite. The series of strata here is (NATHORST 1877, 263):

Andrarum limestone	0,6 m[1]
Alum shale with *Paradoxides davidis* (?)	13,0 ?
Coronatus limestone (=Exsulans limestone)	0,17+
Shale	0,43
Limestone with phosphorite (Fragment limestone)	0,07
Shale	1,5
Greywacke shale with *Holmia kjerulfi*	
Sandstone	

Macro: The fragment limestone at Kiviks Esperöd is only 7—10 cm thick. Macroscopically it is of the same type as the corresponding rock at Brantevik and Andrarum.

Micro: Under the microscope, too, it shows great similarity to the limestones mentioned. The calcareous fragments occur abundantly as 0,1—3 mm-long fragments in a microcrystalline, almost dense calcite matrix with dark pigment (bitumen). Phosphorite occurs in dark, dense grains and nodules, 0,1—8 mm (fig. 51). Phosphatic shells are common. Grains of quartz, angular, 0,1 mm, are sparsely scattered in the rock. Pyrite occurs sparingly in small cubes. Greyish-brown grains consisting of an extremely fine-crystalline substance are identical in texture, shape, and appearance with the green grains of glauconite in the Brantevik limestone. The grains are also often notched in the periphery by new-formed calcite crystals, as is the case in the Brantevik rock and several other glauconitic rocks. The brown colour, which is due to oxidation of the ferro-component of the mineral, is not unusual in glauconite, although it has seldom been observed in Swedish rocks.

Diagenesis and formation: The phosphoritic fragment limestone at Kiviks Esperöd displays the same texture and diagenesis as the corresponding limestone at Brantevik, and the environment of sedimentation have been the same for both rocks.

Exsulans limestone, Skåne.

The stage with *Paradoxides paradoxissimus* consists largely of alum shale. In its lower part, the zone with *Ptychagnostus gibbus* and *Ctenocephalus* (*Conocoryphe*) *exsulans*, there is, however, a limestone, the Exsulans limestone. This limestone contains several characteristic fossils, and its stratigraphical position is established with certainty, which is scarcely the case with the earlier-discussed fragment and arenaceous glauconite-phosphorite limestones of the Lower and Middle Cambrian.

[1] Thickness according to GRÖNWALL 1902, p. 179.

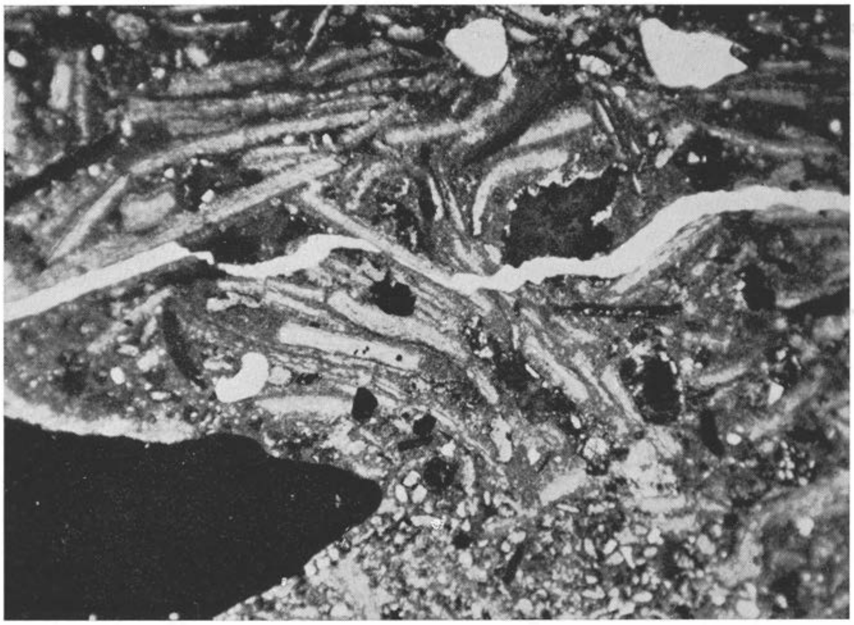

Fig. 51. Fragment limestone with phosphorite (black). Middle Cambrian. Kiviks Esperöd, Skåne. (Prep. 2029, photo 1742.) — 20 ×.

The Exsulans limestone of Skåne is known from Andrarum, Kiviks Esperöd, Brantevik, Gislövshammar (drilling-core), and Södra Sandby. Its lithological development in these places is largely uniform.

Macro: Exsulans limestone is grey, generally with irregular dark, almost black portions alternating with somewhat lighter ones. The latter are clearly crystalline, the dark portions dense. The weathering-crust is light grey or greyish-brown. Pyrite occurs generally in the rock, not infrequently in aggregates of one centimetre. Whole carapaces and large fragments of trilobites are not uncommon.

Micro: The matrix consists of grains of calcite, which measure 20 μ in the dark portions, 40—100 μ in the light (fig. 52). The calcite crystals are separated by a thin bitumen coating in the same way as in dense anthraconites. Fragments of trilobites occur rather abundantly but not by a long way so accumulated as in the earlier described limestones. The fragments are completely recrystallized and surrounded by radiated calcite crystals. Phosphorite does not occur in the specimens examined, neither does glauconite. Quartz occurs sparingly in the rock at Kiviks Esperöd; the grains are angular, 0,1 mm large.

Diagenesis: Both the matrix and the fragments are completely recrystallized.

Formation: The absence of any demonstrable accumulation of fragments and allochthonous minerals (phosphorite, glauconite, quartz) shows that the Exsulans limestone was deposited as calcareous mud, primarily containing fragments in the

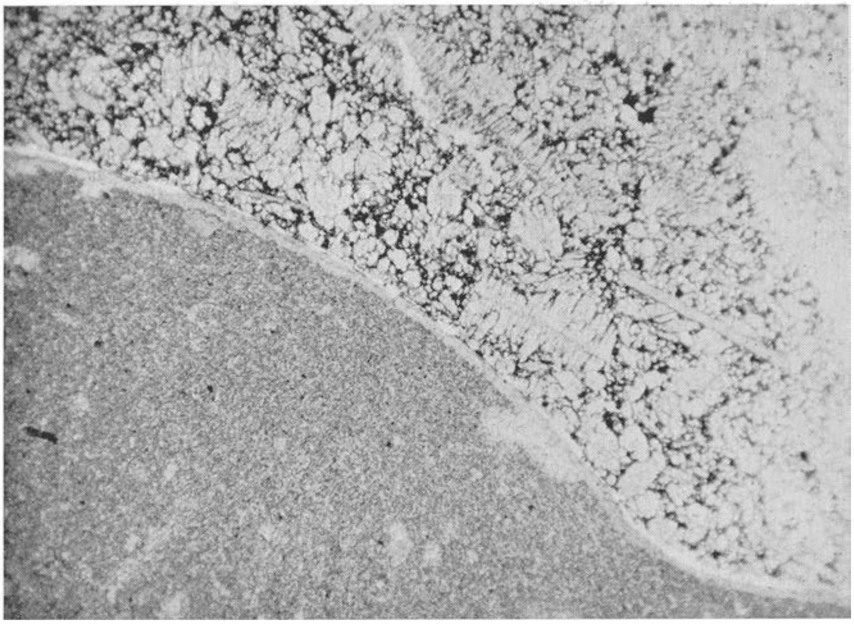

Fig. 52. Exsulans limestone. Lower part dense, dark, upper part light, recrystallized fragment limestone. At the boundary a trilobite carapace. Middle Cambrian. Brantevik, Skåne. (Prep. 7821, photo 1726.) — 20×.

proportion in which they occur in the rock. Sedimentation occurred in quiet water. Deposition was uniform within an extensive area. It indicates that a regionally active factor (increase in temperature?) created the conditions for a spontaneously (from a geological point of view) beginning and short-lived production of calcium carbonate, which resulted in an extended limestone bed interstratified in alum shale. The organic substance which formed the bitumen of the alum shale and which was deposited together with argillaceous mud, is not only met with again in the anthraconites which occur in the alum shale but also in the Exsulans limestone, though in smaller quantity there. The crystalline texture which the limestone acquired through diagenesis is also the same as that occurring in certain anthraconites. The Exsulans limestone can be regarded as a thick, extended, fine-crystalline anthraconite bed.

Andrarum limestone, Skåne.

Among Sweden's Cambrian limestones none is better known than the Andrarum limestone of the upper part of the Middle Cambrian, the stage with *Paradoxides forchhammeri*, the zone with *Centropleura lovéni* and *Solenopleura brachymetopa*. This limestone contains a particularly abundant trilobite fauna, and the deposit at Andrarum was one of ANGELIN's principal localities. The stratigraphic designation

Fig. 53. Andrarum limestone. Dense, dark-grey and crystalline, black, bituminous fragment limestone. Middle Cambrian. Andrarum, Skåne. (Prep. 6561, photo 1725.) — 20×.

Andrarum limestone for limestones belonging to the above zone was adopted after this classic locality.

In Skåne Andrarum limestone has been found at Andrarum, Kiviks Esperöd, Baskemölla (5 km NNW of Simrishamn), and at Gislövshammar (drilling-core). The limestone has a more or less similar development in all these places.

Macro: The Andrarum limestone is composed of two masses somewhat different in texture: one black, clearly crystalline and the other dark-grey, dense. The latter, grey, lies as lumps or nodules, bands, or irregularly shaped portions in the black. The weathering-crust is grey. Whole carapaces of trilobites and large fragments are found in abundance in certain portions of the rock; in others they are almost entirely absent. Pyrite occurs sparsely. Barytes with shining cleavage-planes has been observed in a few places (prep. 3060).

Micro: The dense, grey portions show a microcrystalline, even-grained texture with grain-size approx. 5 μ (fig. 53). Dark-brown bitumen lies squeezed between clear calcite crystals. Small, thin fragments occur sparsely, and somewhat coarser ones form here and there the outer limit of the nodules. They occur in a way which indicates that the nodules have been corroded and that the corrosion (and the crystallization) was stopped by the carapaces (cf. the Exsulans limestone, fig. 52).

The black portions, which form the matrix of the limestone, consist of rod-shaped calcite crystals, approx. 0,1 mm long, often arranged in broom- or plume-shaped aggregates (fig. 54). Bitumen occurs abundantly between the crystals. Small fragments

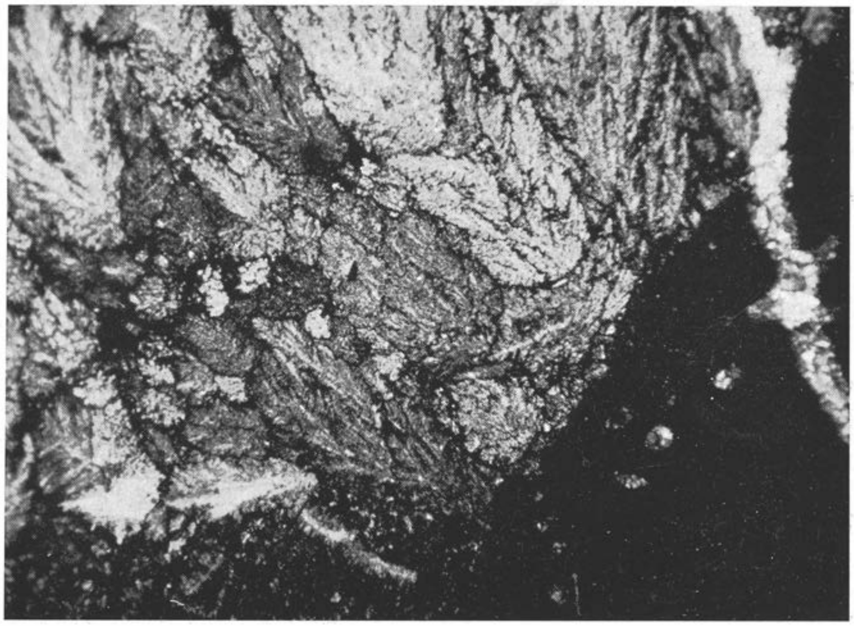

Fig. 54. Fibrous, plume-shaped calcite crystals and microcrystalline, bituminous calcite aggregate. Andrarum limestone, Middle Cambrian. Andrarum, Skåne. (Prep. 6562, photo 1750.) — 20×.

lie thinly scattered in this part of the rock, too. (The large, best preserved trilobite carapaces have been principally observed in the dense rock and on the surface of the nodules.)

Phosphorite and glauconite have not been observed in the Andrarum limestone of Skåne, nor have grains of quartz. Pyrite is only found in negligible quantity.

Formation: Deposition of calcareous mud and fragments together with organic matter in a quiet but not completely isolated basin. Deposition occurred during a temporary decrease in the supply of argillaceous mud to the sedimentation area.

The Andrarum limestone lies as a bed in alum shale. At Andrarum there is another, thinner bed situated immediately beneath the Andrarum limestone and separated from it by a thin stratum of shale. This limestone, Hyolithes limestone[1], is somewhat different in lithologic character from the overlying Andrarum limestone.

The Hyolithes limestone, Andrarum.

Macro: Grey, crystalline limestone, very fossiliferous with small brachiopods and *Hyolithes* shells, etc. (From this bed of limestone Holm (1893, p. 15) mentions no

[1] Tullberg (1882, p. 16). Linnarsson introduced (in manuscript) the designation "Hyolithus limestone".

Fig. 55. Hyolithes limestone. Microcoquina with bituminous matrix and phosphatic nodules (left) and shells. Middle Cambrian. Andrarum. (Prep. 8764, photo 1737.) — 20×.

less than nine species of *Hyolithes*.) Pyrite occurs in cracks and as coating, but only in small quantity. Macroscopic phosphorite has not been observed in the rock.

Micro: Even-grained, microcrystalline with calcite grains of about 30 μ surrounded by a thin brown coating of bitumen. Fragments of calcareous fossils, sometimes completely recrystallized, sometimes unaltered, occupy about 20 % of the mass (fig. 55). Small phosphatic shells (brachiopods) lie scattered in the rock. Phosphorite occurs as authigenic inclusions in and impregnations of the calcareous fragments as well as in small irregular accumulations. There are no grains of quartz or glauconite.

Formation: The Hyolithes limestone has been formed as normally deposited calcareous mud with embedded fossils and precipitated calcium phosphate.

The Middle Cambrian limestones of Bornholm (Denmark).

The Middle Cambrian series of strata on Bornholm contains some limestone beds which correspond directly to those of Skåne (Grönwall 1902 and 1916). The series of strata is exposed at Öleaa and Laesaa, and it is more or less similar in the two places. The series of strata is shown in the adjoining section, fig. 56.

An exhaustive report on the Middle and Upper Cambrian sediments of Bornholm has been made by Kaj Hansen (1945). The conditions of formation, stratigraphic factors, and paleographic data of the rocks have also been discussed by Hansen.

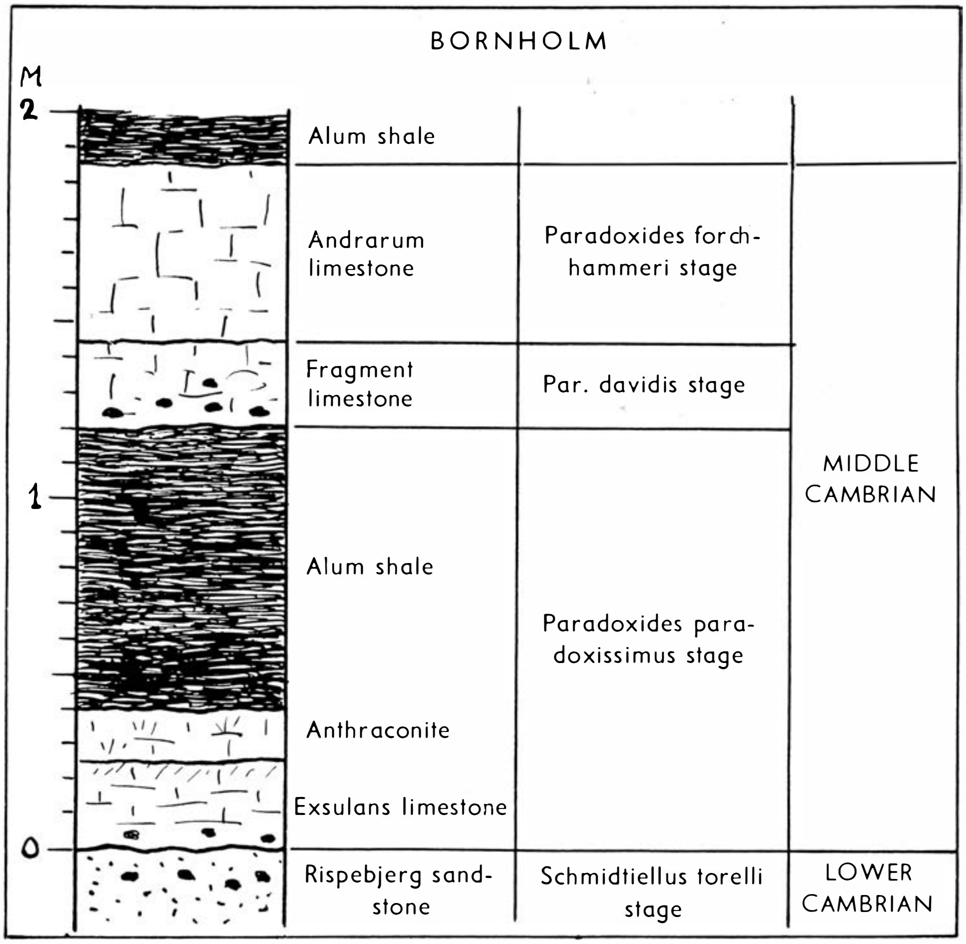

Fig. 56. Section through the Middle Cambrian of Bornholm.

These accounts will not be reported here. Instead a few details will be given of the character of the Bornholm limestones in comparison with the development of the corresponding limestones of Skåne.

The Exsulans limestone of Bornholm.

Macro: The Exsulans limestone of Bornholm can best be studied at Öleaa. (At Laesaa it is much weathered.) The rock appears macroscopically to be a grey or greenish-grey, microcrystalline limestone with rounded, dense, black phosphatic nodules and small green grains of glauconite.

Micro: Matrix microcrystalline, granular (grains 5—15 μ). Trilobite fragments occur abundantly in broken pieces about 1 mm long (fig. 57). Phosphatic shells,

Fig. 57. Exsulans limestone. Matrix microcrystalline. Fragments of trilobite. Glauconite grains mostly replaced by calcite aggregates, fragments of phosphorite (grey), quartz grains and pyrite. Middle Cambrian. Borregaard, Öleaa, Bornholm. (Prep. 6873, photo 1466.) — 20×.

small and thin, occur only scantily. Quartz is found in scattered, well rounded grains, 0,5—1 mm. Glauconite is common in grains of less than 1 mm. In most cases the glauconite grains are more or less replaced by crystalline, pure calcite. The numerous small calcite aggregates which occur scattered throughout the rock, are undoubtedly completely transformed glauconite grains. Best preserved are the glauconite grains which have a coating of phosphorite. Phosphorite is found partly as macroscopic balls, partly as small, angular or rounded grains and lumps. Phosphorite also occurs as a coating on grains of quartz and glauconite.[1] Pyrite in crystals and small aggregates.

Diagenesis: Apart from a general recrystallization and the fact that the glauconite has partly been replaced by calcite the rock has not undergone any appreciable changes after deposition.

Formation: The Exsulans limestone of Bornholm differs from the Exsulans limestone of Skåne in its content of phosphorite, glauconite, and large, rounded grains of quartz. The phosphatic nodules, occasionally interspersed with grains of quartz, appear secondarily and give certain portions of the rock a conglomerate-like character. The Exsulans limestone of Bornholm was formed in at times turbulent water, which transported and accumulated fragments, grains of quartz and glau-

[1] The uppermost 4 cm of the Exsulans limestone are less rich in glauconite and completely without phosphorite, according to Kaj Hansen (1945, p. 9 ff.).

conite but at times permitted sedimentation of calcareous mud. The lithologic character of the rock is largely the same as that of the somewhat older grey phosphoritic, glauconitic fragment limestone at Brantevik. Is it possible that the lower part of the Exsulans limestone of Bornholm corresponds to the fragment limestone of Brantevik? POULSEN (1942, pp. 223 and 232) has shown that the Exsulans limestone of Bornholm contains resedimented fossils from older Cambrian sediments (e. g. *Hyolithellus micans* from the Lower Cambrian and *Acrothele granulata* from the Middle Cambrian).

Fragment limestone, Bornholm.

Both at Laesaa and Öleaa the Andrarum limestone is underlain by a 20—25 cm-thick limestone bed of varying development. The lowermost and middle portions are rich in phosphatic nodules and may be called phosphorite conglomerates (GRÖNWALL 1902, p. 11 ff.); the upper part, which has the character of anthraconite, has no phosphatic nodules. Between the anthraconite and the Andrarum limestone there is a thin layer of fragment limestone (Laesaa) or alum shale (Öleaa). The phosphorite conglomerate and the anthraconite belong to the zone with *Paradoxides davidis*, and the fragment limestone is regarded by GRÖNWALL as a transitional stratum between the Davidis and the Forchhammeri zones. It contains fossils from both these zones (GRÖNWALL 1902, p. 12). A specimen of the fragment limestone was examined.

Macro: The rock is grey, microcrystalline with black, dense phosphorite. Fragments of trilobites and brachiopods (e. g. *Acrotreta*) occur abundantly. Pyrite in small crystals.

Micro: The ground-mass is even-grained with calcite crystals 5—20 μ, separated by bitumen. The fossil fragments, mostly 1—3 mm large, together with small simple sponges (?) occupy about 30—40 % of the mass (fig. 58). Most of the fragments are composed of calcium carbonate (trilobites), and they are often corroded or surrounded by calcite crystals. The sponges are generally impregnated with phosphorite. The phosphatic shells are thin and small. Phosphorite occurs partly as diffuse aggregates or lumps with enclosed calcite crystals and fragments, partly as faecal pellets, 0,1—0,2 mm. Glauconite has been observed in grains (0,4 mm), cracked, allothigenic. There are no grains of quartz in the specimen examined, but they may occur in the rock, according to KAJ HANSEN (1945, p. 25 ff.), who also mentions barytes "in rather considerable quantities".

Formation: The limestone below the Andrarum limestone was deposited during washing-away of mud and accumulation of fragments. The phosphorite in the rock is authigenic, precipitated partly as impregnation, partly in flocks, lumps, and nodules. Whether secondary phosphorite occurs also has not been evident from the investigation. Phosphatic shells occur so abundantly in the rock and are so greatly decayed that the phosphorite must originate from them. (Concerning the phosphorite in this rock see also DEECKE 1897.)

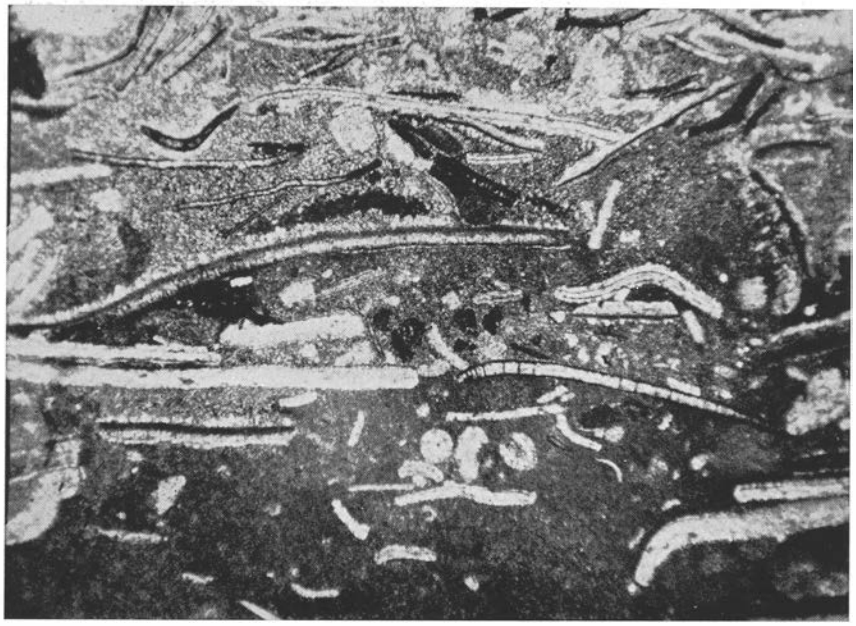

Fig. 58. Fragment limestone. Matrix microcrystalline, bituminous. Trilobite fragments and simple sponges (?). Middle Cambrian. Laesaa, Bornholm. (Prep. 8765a, photo 1753.) — 20×.

The Andrarum limestone of Bornholm.

The Forchhammeri zone of Bornholm contains a limestone bed which corresponds stratigraphically to the Andrarum limestone of Skåne. It is most readily accessible at Laesaa and Öleaa.

Macro: Dark-grey, generally dense portions (nodules) enclosed in a clearly crystalline, darker ground-mass. Large fragments of trilobites occur in certain parts of the rock. A few small aggregates of pyrite. Dense, black phosphatic nodules lie scattered in the rock.

Micro: The dense portions (nodules) consist of small grains of calcite, in certain cases less than 10 μ (prep. 6877), in other cases approx. 0,1 mm, separated by a thin, brown coating of bitumen (fig. 59). The nodules are free from the inclusions (quartz, glauconite) which occur in the surrounding ground-mass.

The dark ground-mass consists of grains of calcite, 0,2—0,3 mm, rounded grains of quartz, 0,1—0,6 mm, scattered grains of glauconite, approx. 0,15 mm, small pyrite aggregates, and phosphorite, partly in the form of small rounded grains (coprolites), 0,2—0,3 mm, partly larger aggregates, 3—11 mm. The latter are sometimes homogeneous, sometimes porous and composed of small phosphatic grains. Fragments of trilobites occur only sparingly, apart from the macroscopic carapaces.

Diagenesis: The rock has undergone fairly strong diagenetic transformation, in which even the fragments have been recrystallized and in certain cases silicified.

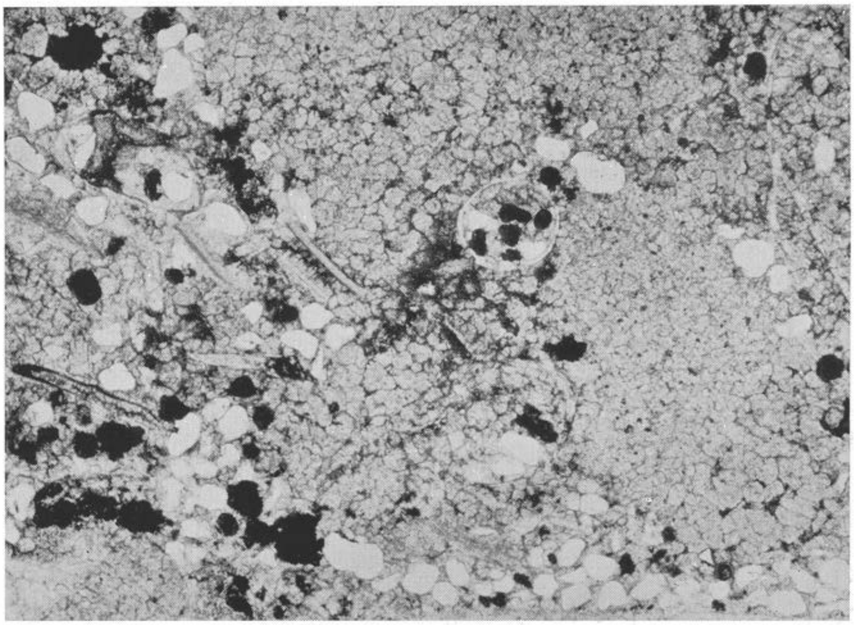

Fig. 59. Andrarum limestone. Microcrystalline, bituminous. Nodules without, matrix with grains of quartz and pyrite. Middle Cambrian. Laesaa, Bornholm. (Prep. 6563, photo 1467.) — 20×.

Formation: The Andrarum limestone of Bornholm differs from that of Skåne in its content of phosphorite, glauconite, and quartz. It has been formed in more turbulent water.

The Middle Cambrian limestones of Västergötland.

Extended limestone beds occur in the Cambrian of Västergötland only at the boundary between the Paradoxissimus and the Forchhammeri stages (see section, fig. 60). The thickness and development of the limestones vary from place to place.

Concerning the lowermost of the Middle Cambrian limestones WESTERGÅRD (1946, p. 16) writes: "Upwards the (*Par. paradoxissimus*) stage terminates in a practically continuous 0,4—0,8 m thick band of greenish, dark-grey or black stinkstone". At Gudhem, where the bed according to WALLERIUS (1895, p. 14) has a thickness of 0,7 m, the lower part of the limestone is bituminous, fine-grained, grey, with a few carapaces of trilobites, e. g. *Par. paradoxissimus.* In the upper part it is conglomeratic, and it grades directly over into the basal bed of the Forchhammeri stage, the Exporrecta conglomerate. A specimen of the rock which WALLERIUS collected at Djupadal and reported as belonging to the (Tessini) Paradoxissimus stage has been examined.

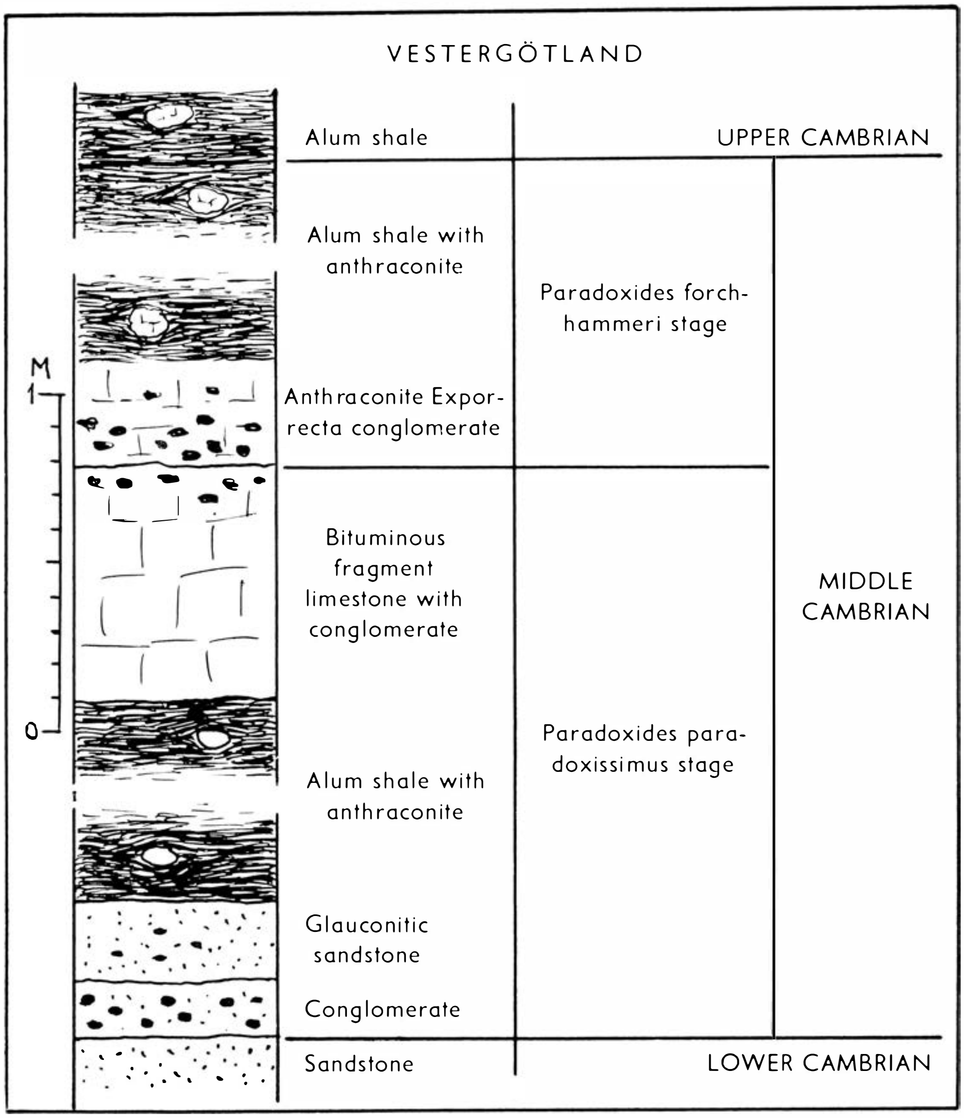

Fig. 60. Section through the Middle Cambrian of Västergötland.

Bituminous fragment limestone, Djupadal, Västergötland.

Macro: The rock is dark-grey, microcrystalline, with numerous, large, thick fragments of trilobites. On weathered surfaces the conglomeratic structure emerges with pebbles of granular limestone, which together with the coarse fragments occupy the major part of the rock mass.

Micro: The ground-mass consists of calcite crystals, 4—15 μ, partly faintly, partly strongly pigmented with bitumen. On impact the rock gives off a strong petroleum smell. Lumps of bitumen enclosed in radiated, clear calcite are characteristic of the rock (fig. 61). The fossil fragments are partly recrystallized, partly lacking in any appreciable secondary transformation. There is no glauconite or phosphorite.

Formation: The conglomeratic limestone has been formed through disintegration and resedimentation of bituminous calcareous mud and limestone (anthraconite); to judge from the varying nature of the material, in various relays. Primarily the sediment was partly formed under the same conditions as anthraconite beds.

Exporrecta conglomerate, Gudhem, Västergötland.

Macro: Conglomerate with pebbles of anthraconite and phosphorite in a relatively small quantity of dense matrix with abundant brachiopod shells, e. g. *Orthis* (*?Oligomus*) *exporrecta*. The fossils of the matrix belong to the fauna of the Andrarum limestone (Forchhammeri stage); the fossils of the pebbles are all older (belonging to the Paradoxissimus stage).

Micro: The pebbles of fine-crystalline, even-grained stinkstone (fig. 62). The ground-mass of microcrystalline calcite and abundant fragments (calcareous and phosphatic shells), grains of glauconite, phosphorite, and a few of quartz (0,1 mm). The glauconite occurs abundantly partly as clear green grains, 0,01—0,4 mm large, partly as impregnation in and coating on pebbles and shell fragments. The glauconite is partly authigenic, partly allothigenic. Phosphorite occurs both in the pebbles and as small flocculent aggregates, occasionally clearly formed from phosphatic shells. Its presence in these cases is primary. There is practically no pyrite (prep. 2556, 6606, 7806, and 7807).

Formation: The conglomerate has been formed by disintegration of consolidated limestone belonging to the Paradoxissimus stage. The matrix with glauconite, quartz, and fossil fragments has been deposited in turbulent water. The phosphorite of the matrix has been formed from phosphatic shells during diagenesis.

The Middle Cambrian limestones of Öland.

The Cambrian series of strata of Öland contains sandstones, shales, and alum shales of great thickness. Calcareous sediments are found mostly in the form of calcareous sandstones and anthraconite. In the Middle Cambrian, however, there are thin beds of limestone and limestone conglomerate (see section, fig. 63). They represent periods during which the depth of the water was decreased and its turbulence (wave-movement and currents) increased. The limestone conglomerates also indicate negative sedimentation (disintegration and partial washing-away of deposited layers), and they represent breaks in the series of strata. Below four different limestones are mentioned: 1) an arenaceous limestone in the stage with *Paradoxides oelandicus*, 2) the calcareous conglomerate with *Acrothele granulata*, 3) the Exsulans limestone, and 4) the Exporrecta conglomerate.

Fig. 61. Bituminous fragment limestone. Middle Cambrian, Djupadal, Västergötland. (Prep. 6604, photo 1744.) — 20×.

Fig. 62. Conglomeratic limestone. Pebbles of anthraconite (lower left), matrix of microcrystalline calcite, calcareous and phosphatic fossil fragments, glauconite, and phosphorite. Exporrecta conglomerate, Middle Cambrian. Gudhem, Västergötland. (Prep. 7806, photo 1745.) — 20×.

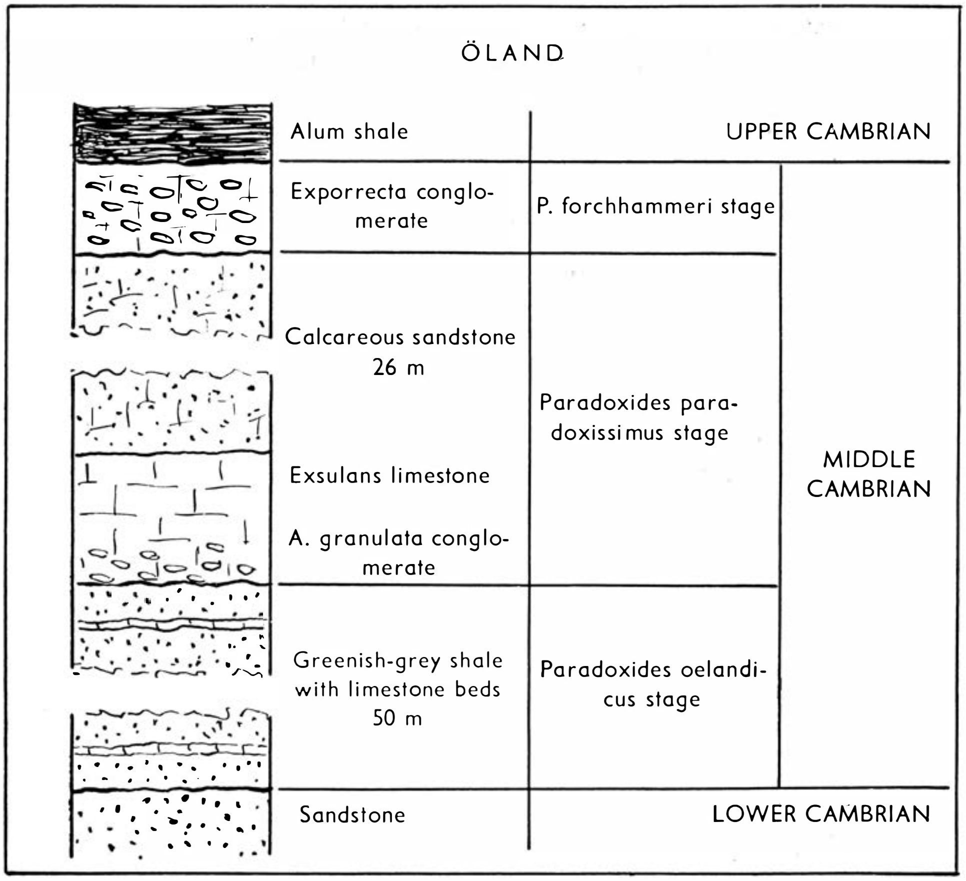

Fig. 63. Section through the Middle Cambrian of Öland.

1) *Arenaceous limestone, Strandtorp, Öland.*

The Paradoxides oelandicus stage of Öland is about 60 m thick and largely composed of sandstones and arenaceous, greenish-grey shales. The percentage of calcium carbonate of these rocks varies and increases in scattered niveaux so that arenaceous limestones are formed. As the type for these an arenaceous limestone from Strandtorp, south of Borgholm, will be presented.

Macro: Dense, rough, dull greenish-grey limestone with scattered trilobite fragments. The weathering-crust is greyish-brown.

Micro: The limestone consists of a fine-crystalline calcite aggregate (grains 0,1—0,2 mm) and small, angular grains of quartz (0,02—0,04 mm), the latter 10—20 % of the mass (fig. 64). Green grains of glauconite (0,03—0,1 mm) are found scattered in the rock, also grains of pyrite. The extremely rare trilobite fragments are corroded.

Diagenesis: Complete crystallization of the calcite mud, but without formation of large crystals.

Formation: Deposition of well-sorted, small grains of quartz together with (allothigenic) glauconite and calcareous mud in slightly turbulent, not entirely shallow water. Neutral environment.

2) *The Acrothele granulata conglomerate, Köping, Öland.*

Macro: The conglomerate at the base of the Par. paradoxissimus stage consists of rounded pebbles of fine-grained limestone and calcareous sandstone, often strongly impregnated with green glauconite. The ground-mass contains abundant shell fragments and grains of quartz and glauconite.

Micro: The rock contains abundant phosphatic shells and small lumps of phosphorite (3 mm) (fig. 65). Glauconite occurs as impregnation not only in the calcareous pebbles but also in the fossil fragments. Glauconite is also found as diffuse, authigenic masses or small, irregular grains, and as large, round, allothigenic grains (0,7 mm). Rounded grains of quartz 0,2—0,7 mm. Thin layers of the rock contain only small angular grains of quartz (0,01—0,05 mm), no larger grains of quartz or glauconite (fig. 65).

Formation: The calcareous conglomerate is a shallow-water deposit. For its formation and glauconite-content see HADDING 1927, p. 74 and 1932, p. 81 etc.

3) *Exsulans limestone, Risinge, Öland.*

At the base of the series of calcareous sandstones which overlie the conglomerate with *Acrothele granulata* in Öland there are a number of beds with abundant calcareous fossils. The ground-mass is always arenaceous, but the percentage of calcite so high that the rock can be termed arenaceous limestone. The rock corresponds to the Exsulans limestone of Skåne. The arenaceous limestone at Risinge, south of Mörbylånga, has been chosen as an example.

Macro: Dark greyish-green limestone, mottled with dark-brown or black trilobite fragments and green patches of glauconite. Bed 30 mm with even bedding planes.

Micro: Ground-mass of granular calcite, greatly but irregularly interspersed with small, angular grains of quartz (0,06 mm) and occasional larger, rounded ones (fig. 66). Glauconite is found as green grains (0,1—0,6 mm) and as impregnation in fossils and in small, dense limestone pebbles (of the same type as those in the underlying conglomerate but only a few millimetres in diameter). Phosphorite in scattered pellets. Phosphatic shells of brachiopods. Pyrite in small crystals and aggregates. Fossil fragments occur abundantly (trilobites etc.), often impregnated with pyritic dust.

Diagenesis: Complete crystallization of the calcareous mud.

Formation: Deposition of fragments and well separated grains in slightly turbulent water with neutral or weakly reducing environment.

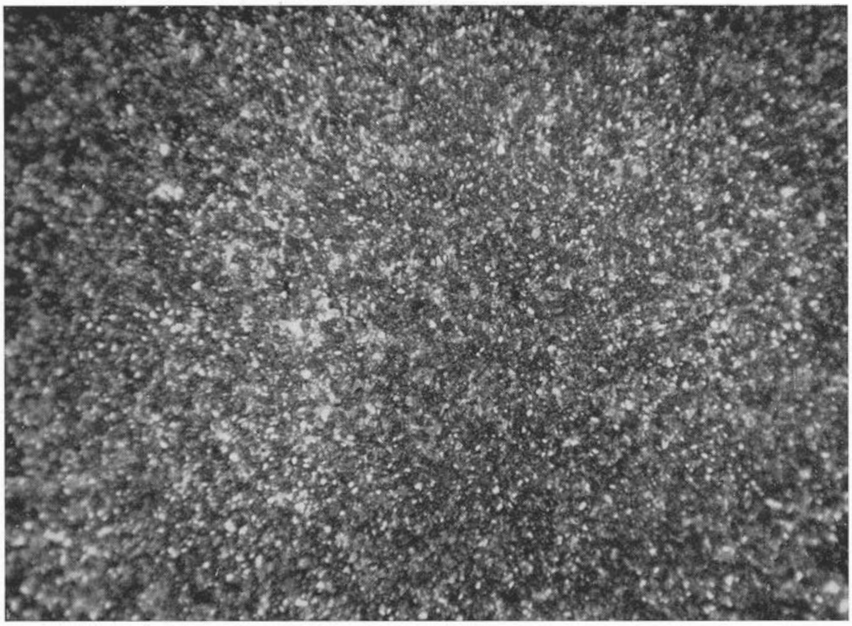

Fig. 64. Arenaceous limestone. Middle Cambrian. Strandtorp, Öland. (prep. 7381, photo 1756.) — $20\times$.

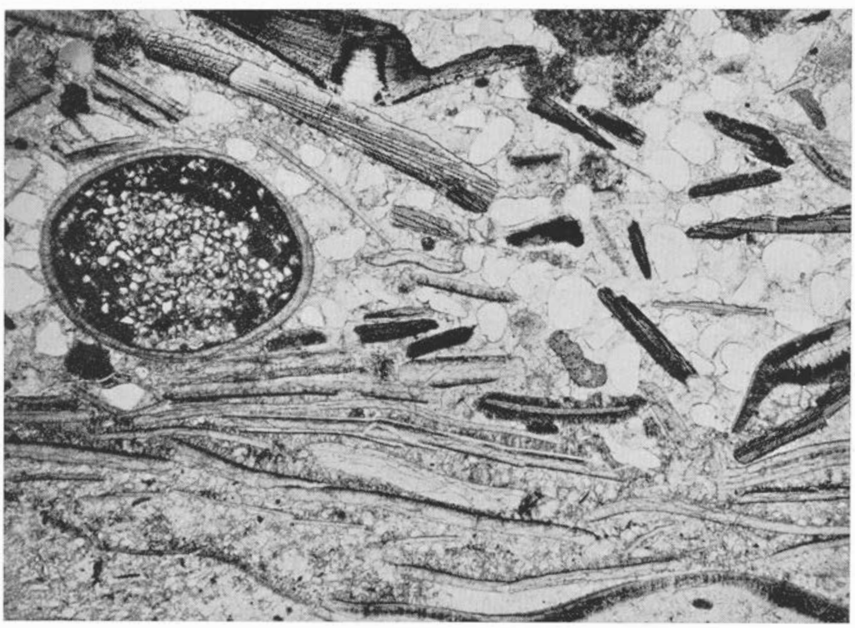

Fig. 65. Conglomeratic limestone. Matrix microcrystalline, with calcareous and phosphatic shell fragments, grains of quartz and glauconite, lumps of phosphorite. Granulata conglomerate, Middle Cambrian. Köping, Öland. (Prep. 7519, photo 1382.) — $20\times$.

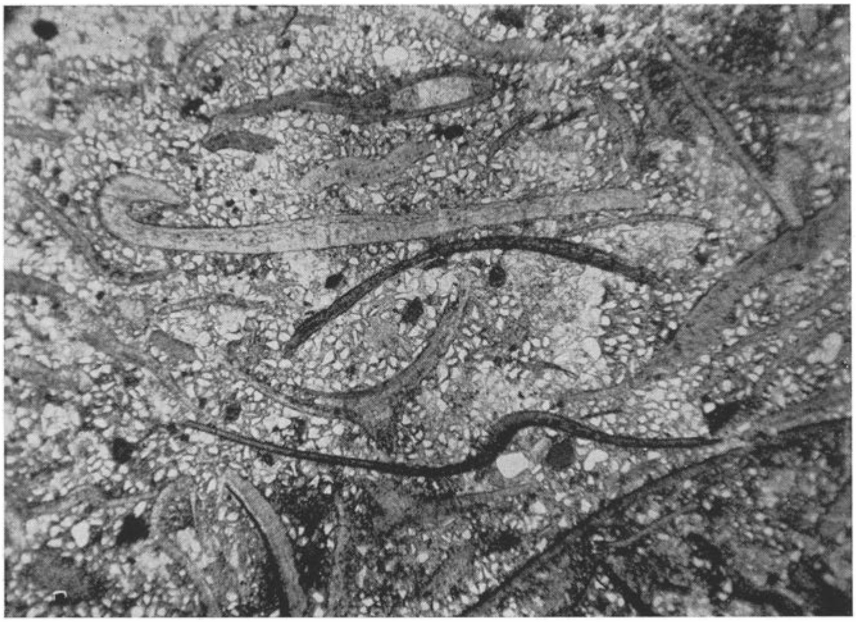

Fig. 66. Exsulans limestone. Arenaceous fragment limestone. Middle Cambrian, Risinge, Öland. (Prep. 3190, photo 1746.) — 20 ×.

4) *Exporrecta conglomerate, Köping, Öland.*

In several places in Öland there is a conglomerate between the uppermost calcareous sandstone of the Paradoxissimus stage and an anthraconite bed with *Agnostus pisiformis*. The conglomerate contains *Agn. pisiformis* both in the pebbles and in the matrix (WESTERGÅRD 1946, p. 15), but it has been ranked with the Exporrecta conglomerate, which replaces the Andrarum limestone in several parts of Sweden. Fragments of *Oligomus exporrecta* (?) are also mentioned from the Ölandian conglomerate.

Macro: Bed of very varying development, partly anthraconitic. The conglomerate has a greenish-grey, fine-grained matrix. The pebbles are mostly disc-shaped, oval. They attain a diameter of several centimetres. They are of varying nature: shale, sandstone, arenaceous limestone, calcareous sandstone, anthraconite, and phosphorite. A remarkable fact is that the pebbles entirely lack glauconite impregnation.

Micro: The ground-mass of the conglomerate is composed of partly coarse-crystalline, partly fine-crystalline calcite, bitumen, and small grains of quartz (fig. 67). (For other details of the conglomerate see HADDING 1927, p. 78).

Formation: The calcareous sediment which forms the ground mass of the Exporrecta conglomerate has been formed in shallow and quiet water, after the pebbles of the conglomerate were finally shaped. The formation of the calcareous sediment occurred after the land-subsidence began which later resulted in deposition of the

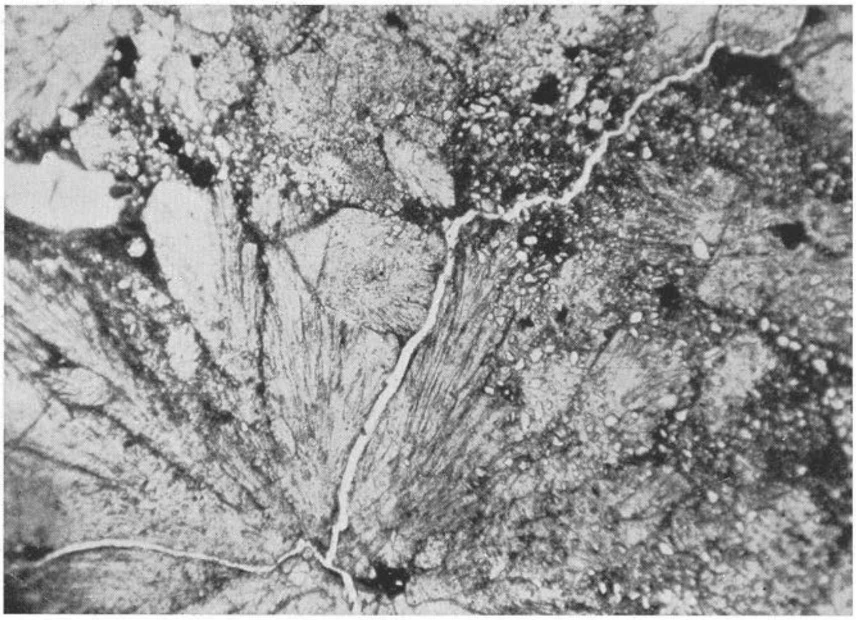

Fig. 67. Exporrecta conglomerate. Matrix bituminous, arenaceous, with coarse-grained calcite. Middle Cambrian. Köping, Öland. (Prep. 3244, photo 1747.) — 20×.

mud which formed the alum shale. The Exporrecta conglomerate clarifies the changes in the environmental conditions under which the limestone beds in the shale series were formed.

Limestones occur in the Middle Cambrian series of strata in several places in central and northern Sweden's Cambro-Silurian field. No deviations from the south-Swedish types have been observed, for which reason they will not be considered in this context.

Upper Cambrian limestones.

The Upper Cambrian of Sweden consists of black, bituminous shales, alum shales,[1] with balls, lenses, and beds of bituminous limestone, anthraconite.[2] The percentage of anthraconite in the alum shales varies. It is small in the thickest series of shale (Andrarum: shale 40 m, anthraconite 4 m. Lanna: shale 13,5 m, anthraconite 2,1 m). In these sections the anthraconite is developed as scattered balls. Beds and lenses of anthraconite are best developed where the series of alum

[1] Black, bituminous shales are called alum shales if they show a black, glossy streak.

[2] All bituminous, macro- and microcrystalline limestones of the alum shales are here called anthraconite.

shale is thin and incomplete (with breaks). In most places there is a bed, about 1 m thick, in the lower part of the section (zones with *Olenus* and *Parabolina spinulosa*).

Anthraconite is found in younger alum shales, too, e. g. Lower Ordovician (Dictyonema shale) and Lower Silurian (Rastrites shale). The character of the rock does not change.

Anthraconite — Stinkstone.

The alum shales of the Middle and Upper Cambrian and Lower Ordovician contain at various levels nodules, balls, or beds of bituminous limestone, anthraconite. Mostly this is dark-black or dark-brown, more seldom light, greenish-grey. It gives off a characteristic petroleum smell from fresh fracture-faces and on impact, and it is therefore with good reason called stinkstone. Macroscopically crystalline forms, granular or radiated, are of the same character as the microcrystalline forms, as regards primary nature and formation. All of them are grouped here under the common designation of anthraconite.

Although the anthraconites are concretionary and thus secondarily formed limestones, they have nevertheless only come into being thanks to primary calcareous deposits. What these were like, under what conditions they were formed, and the cause and method of their secondary transformation are problems which are intimately associated with the formation of limestone in general.

Primary sedimentation of anthraconite calcium carbonate.

To judge in what form and way the calcareous matter of the anthraconites was sedimented, it is necessary to study the series of strata and the special features these may possibly display in anthraconite horizons. Broadly speaking, the anthraconites belong to the alum-shale series, and, like them, their calcareous matter has been formed in relatively isolated basins. The calcium carbonate has primarily formed part of argillaceous mud rich in organic matter. Fossil fragments (especially trilobites and brachiopods) occur here and there in the alum shales and in the anthraconites, in certain layers so profusely that they cover the bedding planes, but the calcium carbonate of the anthraconites cannot originate from these shells entirely. It is particularly evident that the larger deposits of anthraconite, the occasionally rather extensive and thick beds, must have been formed from highly calcareous mud. What this calcareous mud was like, whether it consisted of organically or inorganically precipitated calcium carbonate, cannot be determined from a study of the always crystalline and secondarily formed anthraconites.

Even if it is not possible to determine the form in which the calcium carbonate of the anthraconites was sedimented primarily, it is nevertheless evident that the deposition of calcium carbonate took place under certain conditions which left their mark on the rock. Particularly remarkable is the fact that anthraconite beds regularly occur in conjunction with the intraformational conglomerates of the alumshale series.

The shape, size, composition, structure, and appearance of the anthraconites.

Shape. Freely developed anthraconites in the alum shale are generally shaped like a more or less compressed sphere, an ellipsoid, with the major axis parallel to the bedding planes of the shale. The relation between the major and the minor axes is variable. Coalescence of two or more anthraconites may give the concretion a more irregular shape. Lenses and out-thinning beds of anthraconite are of varying thickness and extent, often because they comprise a number of concretions formed around different centres.

Size. The regular, round anthraconites vary in size from a few centimetres to about one metre. The beds (lenses) may have an extent of several metres.

Composition. Essential constituents of anthraconite are calcium carbonate, argillaceous matter, and bitumen. A "normal" proportion between these three substances is 88—10—2, but the variations may be quite large. The most common occasional constituents observed are quartz, pyrite, phosphorite, glauconite, and barytes.

The calcium carbonate of the anthraconites is principally secondarily formed calcite in crystals and aggregates of varying shape and size. In addition to this calcite, concretionarily accumulated during diagenesis of the rock, the anthraconites sometimes contain calcium carbonate in the form of fossil fragments (trilobites and brachiopods) and occasionally layers with limestone pebbles or rounded (worn) calcite grains, too. In the latter cases the anthraconite concretion has been formed around a conglomerate-like or granular calcareous sediment (Köpings klint, Öland; Bruddestad, Öland; Gudhem, Västergötland; Knivinge and Västanå, Östergötland).

The mud-forming part of the anthraconites is of the same composition as the bituminous shales (alum shales), in which the anthraconites are found.

Quartz occurs in the anthraconites only in the form of small angular grains (0,005—0,05 mm). In certain layers the grains of quartz are accumulated, and they are then also found as inclusions in the calcite crystals. As the grains of quartz belong to the primary constituents of the sediments, a detailed investigation of the appearance of arenaceous layers in the anthraconites and surrounding shale should contribute to solving the relationship between these rocks, as regards their compression and shrinking during diagenesis.

Structure and texture. It is not unusual to find a distinct bedding structure in anthraconite (fig. 68). It appears most commonly when the rock is split or falls apart along highly fossiliferous bedding planes (fig. 69). Stratification may also become visible through weathering in apparently purely massive anthraconite.[1]

The texture of the concretions is crystalline-granular or crystalline-radiated. Often both these forms are found in one and the same anthraconite (fig. 70). The

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[1] Occasionally it is possible to identify bedding planes in the anthraconite with corresponding planes in the surrounding alum shale. Where two or more such bedding planes are encountered, the compression of the shale (after the formation of anthraconite) can be calculated. In Ordovician strata a reduction of approx. 85 % has been found (Hadding 1913, p. 25).

Fig. 68. Anthraconite with bedding plane. Upper Cambrian alum shale. Uddagården, Västergötland.

Fig. 69. Anthraconite. Carapaces of trilobites accumulated on a bedding surface. Upper Cambrian. Käpplunda, Västergötland. (Photo 1499.) — $^1/_1$.

Fig. 70. Anthraconite lens, middle part granular, upper and lower part crystalline-radiated. Upper Cambrian alum shale. Käpplunda, Västergötland.

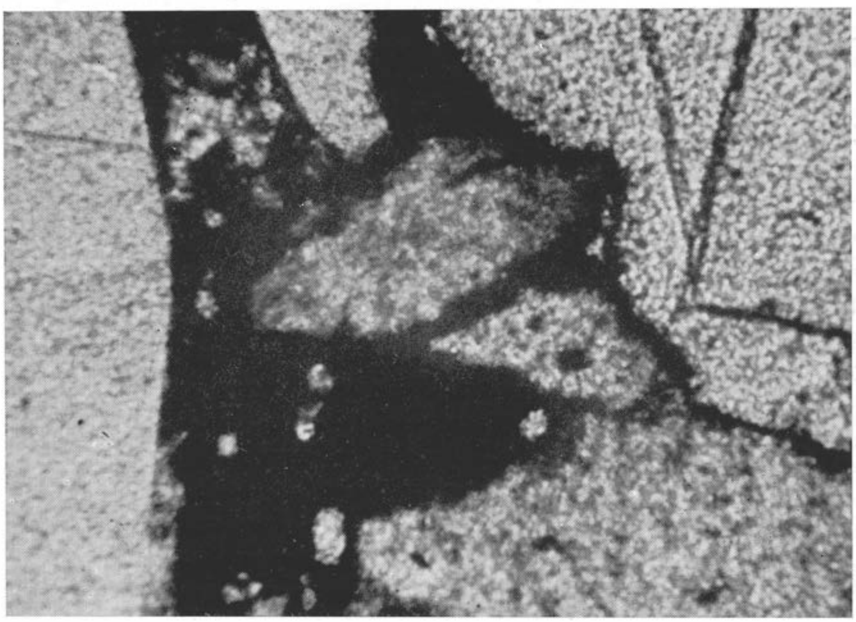

Fig. 71. Anthraconite. Calcite crystals in bituminous-argillaceous mud. Upper Cambrian. Knivinge, Östergötland. (Prep. 7776, photo 1579.) — 60 ×.

organic component of the mud, bitumen, has influenced crystallization of the calcite and given rise to the characteristic texture of the anthraconites.

The granular anthraconites may be macroscopically dense aggregates with calcite grains, 0,01—0,05 mm in diameter. More often, however, the individual crystals are separated by bitumen and are discerned macroscopically through reflections from cleavage-planes. The shape of the crystals varies: sometimes it is isometric (like the rhombohedron), sometimes elongated (like the scalenohedron and prism) or flat (like the obtuse rhombohedron). Natural surfaces rarely occur. The crystals are ragged through contact with the bituminous mass which surrounds the grains and prevents them from coming into direct contact with one another. A remarkable fact is that the calcite during crystallization in the mud pushes back the bitumen-mixed argillaceous mass (fig. 71).

In the fine-grained anthraconites small bands are found here and there with radiated calcite (fig. 72). Sometimes the band has a fossil fragment as a core, in other cases this is missing. The fragment has then been completely dissolved, and only the radiated band shows that a fossil has been there.

Amongst the granular anthraconites we can include, too, the form which contains up to 30 mm-large, isometric, white or colourless crystals scattered in a black or brown, somewhat calcareous matrix. This form has been encountered, for example, in the Olenus shale at Knivinge in Östergötland (fig. 73) and at S. Möckleby, Öland.

In the columnar anthraconites the longitudinal direction of the calcite crystals is the main crystallographic axis. The columns, which are separated from one another by a bituminous coating and easily fall apart (fig. 74), are bounded by longitudinal surfaces without definite orientation and often forming re-entering angles. As the columns have grown on an earlier formed, granular anthraconite ball (fig. 70) or on a conglomerate pebble, they are radiating and have a breadth which increases towards the periphery. In contrast to the small crystals (in the granular anthraconites) the columnar crystals, which can attain an appreciable length, have noticeable inclusions of bitumen and argillaceous mud. Interlaminations occur along the length of the columns with swellings parallel to the cleavage-planes (rhombohedron surfaces). In radiated anthraconites the inclusions may give the crystals features reminiscent of the "cone in cone" texture (fig. 75). These textural forms are, however, essentially different in character and formation (cf. Kaj Hansen 1938).

Pyrite has been observed in many of the Cambrian anthraconites but hardly in the majority. A striking fact is that the mineral only occurs in small quantity and in the form of crystals (cubes) or very small aggregates.

Phosphorite in the form of nodules is found where anthraconites have been formed around phosphoritic conglomerates. Calcium phosphate has, however, also been observed in anthraconites in the form of shell fragments (brachiopod shells), small coprolites, and diffuse aggregates, the latter presumably formed by phosphatisation of calcite. In each case the phosphorite belongs to sediments deposited before the anthraconite was formed.

Grains of glauconite have only been observed in a few cases and then together

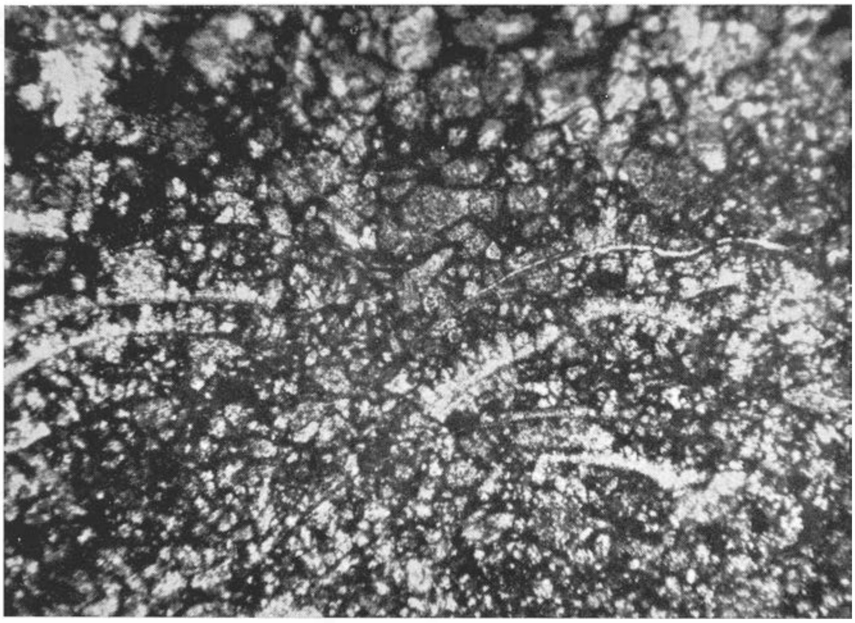

Fig. 72. Anthraconite, fine-grained, with radiating calcite crystals on fossil fragments. Upper Cambrian. Gudhem, Västergötland. (Prep. 6638, photo 1581.) — 13×.

Fig. 73. Anthraconite with calcite crystals scattered in bituminous, calcareous matrix. Upper Cambrian. Knivinge, Östergötland. (Spec. 6011, photo 1578.) — $^1/_1$.

Fig. 74. Anthraconite with columnar calcite crystals. Upper Cambrian. Djupvik, Öland. (Spec. 5407, photo 1573.) — $^1/_1$.

with phosphorite in conglomerates in anthraconites. Glauconite like phosphorite is an older, secondary, and occasionally inclusion occurring in the anthraconites.

Barytes appears in free crystals and concretionary aggregates in the Cambro-Ordovician alum-shale series, particularly in the zone with *Orusia lenticularis* and in the Dictyonema shale. In these parts of the series of strata one may also find pseudomorphs in calcite after barytes, both isolated crystals and concretions (HADDING 1939). The crystal shape of the barytes and also its zonal structure are fully preserved in the secondarily formed, usually fine-grained calcite (Flagabro, Råbäck).

Barytes appears as radiated aggregates in normally developed, fine-grained anthraconite (fig. 76). The barytes of these "stars" is usually unweathered and in the form of sharply pointed prisms. The crystals are not limited to one plane (a bedding plane); they diverge from the centre in all directions. The barytes of these aggregates was formed in the mud before or conjointly with the formation of the anthraconite. (Äleklinta and Grönvik in Öland.)

Fig. 75. Anthraconite. Vertical section through a columnar crystal. Upper Cambrian. Billingen: Västergötland. (Prep. 618, photo 1580.) — 13 ×.

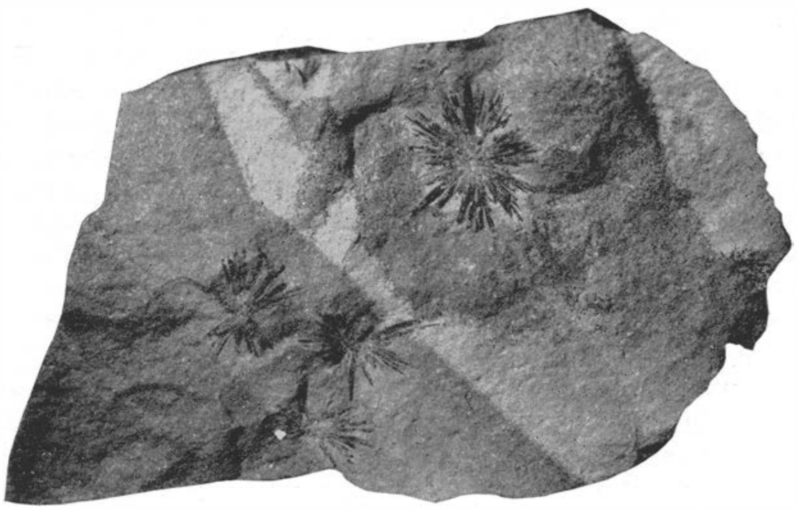

Fig. 76. Barytes stars in fine-grained anthraconite. Upper Cambrian. Djupvik, Öland. (Photo 1583.) — $^1/_1$.

Appearance in the series of strata.

The anthraconites are not restricted to one or a few particular levels of the Cambro-Ordovician series of strata. They are found scattered throughout the greater part of the alum-shale series (see WESTERGÅRD 1922). If an anthraconite is found at a certain level, it can, however, be reckoned that this level contains several in the same area. The primarily deposited, highly calcareous sapropelic mud, the calcium carbonate content of which later went over into the concretions, covered such large areas and formed such extended mud layers that several nodules, lenses, or more extended beds of anthraconite were formed. As a rule the alum shale which surrounds the anthraconites is non-calcareous or only slightly calcareous, and there is no reason to assume that the parts of the shale series which do not contain calcareous concretions were primarily more calcareous than the shale now appears. Transportation of the calcium carbonate which resulted in the formation of concretions chiefly took place horizontally, within one layer, not vertically from one level to another. A concretion which begins to be formed around a core in a calcareous mud layer is not, however, entirely bound to this layer during its growth. In the large ellipsoidal anthraconites (of small extent horizontally) the calcite aggregate has grown far beyond the layer in which formation of the concretion started. Growth has taken place both on the upper and the lower sides. In such a case the concretion may show a stratified structure.

Ordovician limestones.

In contrast to the Cambrian series of strata, which contains few and relatively unimportant calcareous sediments, the Ordovician consists essentially of limestone. Even in the oldest part of the Ordovician a limestone occurs, Ceratopyge limestone. It marks a pronounced change in the lithologic facies where it follows upon the Upper Cambrian or Lower Ordovician alum shale. The younger parts of the Ordovician, the Chasmops, Tretaspis, and Dalmanitina series, also contain limestones, but the thickest limestone series of the formation, the Orthoceras limestone, is found in its next oldest part, the Asaphus series. Considerable lithologic variations occur, however, in the widestretched sedimentation areas.

Lower Ordovician limestones.

<table>
<tr><th></th><th>Öland[1]</th><th>Västergötland</th><th>Skåne</th></tr>
<tr><td rowspan="4">Asaphus series (Orthoceras limestone)</td><td rowspan="2">Platyurus limestone
Gigas limestone
Raniceps limestone
Expansus limestone
Lepidurus limestone</td><td>Upper red limestone</td><td rowspan="2">Upper Didymograptus shale</td></tr>
<tr><td>Lower grey limestone</td></tr>
<tr><td rowspan="2">Limbata limestone
Planilimbata limestone</td><td rowspan="2">Lower red limestone</td><td>Orthoceras limestone</td></tr>
<tr><td>Lower Didymograptus shale</td></tr>
<tr><td>Ceratopyge series</td><td>Ceratopyge limestone</td><td>Ceratopyge limestone</td><td>Ceratopyge limestone</td></tr>
</table>

[1] See also scheme p. 116.

Ceratopyge limestone.

At the boundary between the Cambrian and Ordovician one finds in several places in Sweden a very striking change in the lithological character of the sediments. In the Upper Cambrian, where alum shale dominates, the series of strata is uniformly composed, but great variations occur in the lowermost Ordovician. In some places, and especially in Skåne, the alum shale continues up into the Ordovician (Dictyonema shale), but even where such is the case the series contains limestone beds. Irrespective of its stratigraphical extent this oldest limestone series of the Ordovician is called Ceratopyge limestone (after *Ceratopyge forficula* SARS).

In Sweden the Ceratopyge limestone usually contains glauconite and is often accompanied by glauconitic shale. Its formation can therefore be put in a certain relationship with that of glauconite (see HADDING 1932). However, the limestone shows great variations of development in the different sedimentation areas. The various types will be discussed.

Ceratopyge limestone in Skåne.

Ceratopyge limestone, Flagabro.

In south-east Skåne the earliest Ordovician is represented by alum shale with *Dictyonema*. At Flagabro this shale is found directly superimposed by a black and grey limestone divided up into beds of 3—7 cm thickness (see fig. 77). This strongly marked change of the facies from alum shale to glauconitic limestone and the succeeding gradual transition to normal limestone and shale lend special interest to the series, which will therefore be examined in detail.

The series of strata in its entirety from the Orthoceras limestone to the Upper Cambrian alum shale has recently been drilled at Flagabro, and the core will be subjected to a thorough paleontological and stratigraphical examination. This investigation will be of interest from a lithological point of view, too, one reason being that the series of strata is rich in large barytes concretions in certain parts.

Macro: The lowermost bed, which rests directly upon the alum shale (the Dictyonema shale), is crystalline with fine-grained, dark-grey and more coarsely grained, light-grey parts unevenly mixed with one another. Dense, black phosphorite (partly angular grains and partly uneven cakes) occurs abundantly in the upper part of the bed.

Pyrite aggregates and crystals are spread throughout the whole bed but mainly in its lower part.

Micro: Ground-mass of crystalline calcite with isometric grains, colourless or faintly pigmented. Grain size 0,1—0,5 mm. Occasionally the grains are embedded in dark, bituminous mud. This is always the case where the calcite forms a crust of radiated crystals around an extremely fine-grained core (cf. the texture in bed 2 and fig. 79).

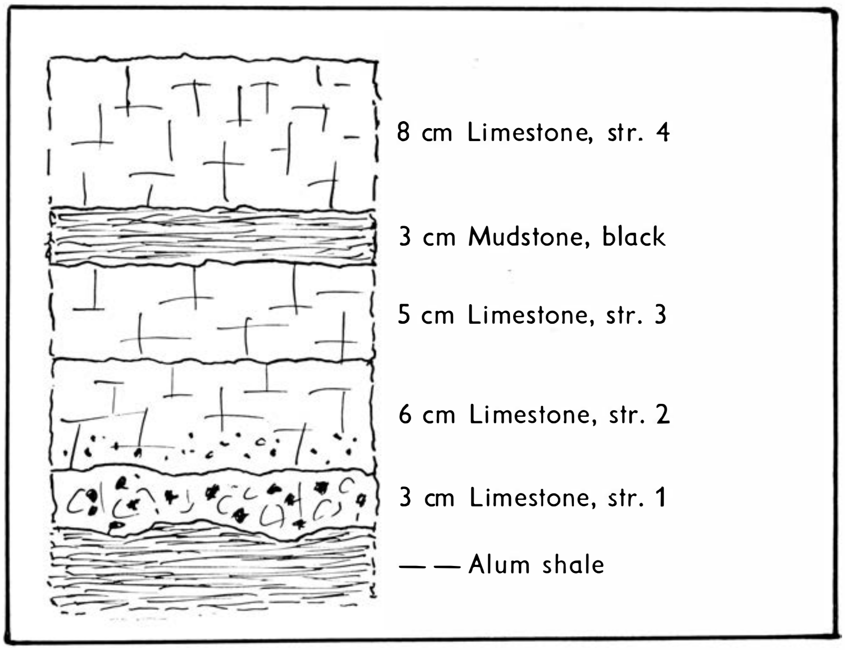

Fig. 77. Section through the Ceratopyge limestone at Flagabro, Skåne.

The phosphorite occurs partly as rounded or angular nodules (diameter about 10 mm), partly as small, irregular grains and very small spherical balls (fig. 78). The latter have a crust of a slightly double-refracting, crystalline substance (chitin) and a core of varying composition: calcite, phosphorite, or in a few cases chalcedony. The thin crust has the same brown colour as the phosphorite. The balls are of organic origin.[1] The phosphorite is sometimes uniform in colour and density, sometimes heterogeneous with lighter portions in a darker, granular mass (see fig. 12, p. 28). Calcite may be present interstitially, but otherwise the phosphorite does not contain any foreign inclusions. It is authigenic. This is also evident from the fact that the rock contains fragments of phosphatic brachiopod shells, at times covered with new-formed, dense phosphorite. An enrichment of the phosphatic nodules may, however, have taken place, and in certain places therefore the limestone has a conglomerate-like appearance. It should be designated *phosphorite limestone*.

Under the microscope glauconite, too, appears as an important constituent of the limestone. The glauconite grains are 0,1—0,6 mm in diameter, irregular but clearly rounded. The colour in transmitted light is a pale yellowish-green. (Under a magnifying-glass the grains appear black on account of a dark superficial impregnation.) In a number of the grains the glauconite has been partly replaced by calcite; the size and shape of the original grains can then be observed from the well-preserved coating of pigment (cf. Hadding 1932, p. 102, figs. 59 and 60).

[1] Regnéll (1955, p. 546) has described the balls as *Leiosphaera* sp.

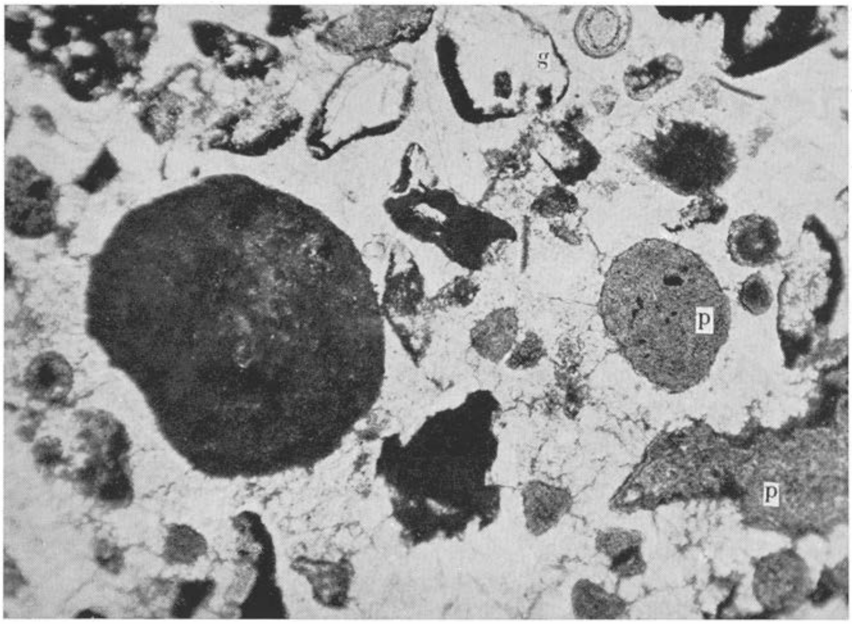

Fig. 78. Ceratopyge limestone. Pellets of phosphorite (p), grains of glauconite (g), and irregularly formed lumps of bitumen in matrix of fine-grained calcite. Lower Ordovician. Flagabro, Skåne. (Prep. 6316, photo 1298.) — 60 ×.

The second (next lowermost) bed of the Ceratopyge limestone at Flagabro is dense, grey, with phosphorite and glauconite together with abundant pyrite, particularly in the lower part of the bed.

Micro: In the lower part of the bed the calcite is well crystallized, partly in radiated aggregates (see fig. 79) round a dense core. The dark, bituminous mud, which primarily was intimately mixed with the calcium carbonate, has been displaced by the crystallization of the calcite and now occupies the space between the calcite crystals. In the upper part of the bed the ground-mass is microcrystalline (grains 0,01—0,03 mm), even-grained, but radiated where bordering on phosphorite lumps or portions of displaced bituminous mud (fig. 80).

Pyrite cubes are found scattered in the calcite aggregates and in the mud portions. Glauconite occurs sparsely in large grains, peripherally replaced by calcite crystals.

The third bed is dense, grey. Pyrite (in finely grained aggregates) occurs as thin lenses in the middle of the bed and as large concretions in the lower part of the bed.

Micro: The calcite appears partly as finely crystalline, granular aggregates, partly as spool-shaped crystals, the latter surrounded by consolidated dark mud (fig. 81). A few small shell fragments are present. They are recrystallized and have a crust of radiated calcite.

Fourth bed. Above the third limestone bed follows a black shale of some centi-

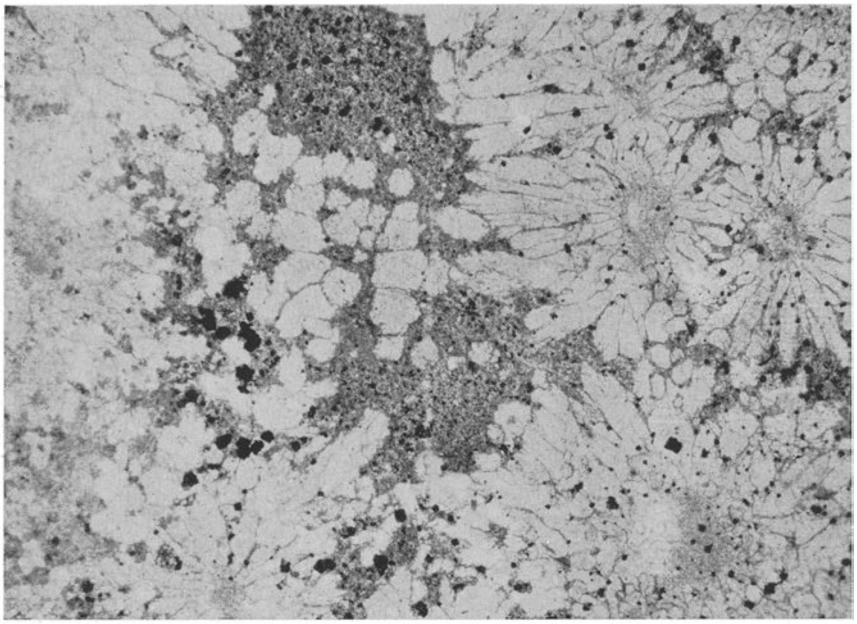

Fig. 79. Ceratopyge limestone. Radiated aggregates of calcite in bituminous matrix. Lower Ordovician. Flagabro, Skåne. (Prep. 6317, photo 1293.) — 20 ×.

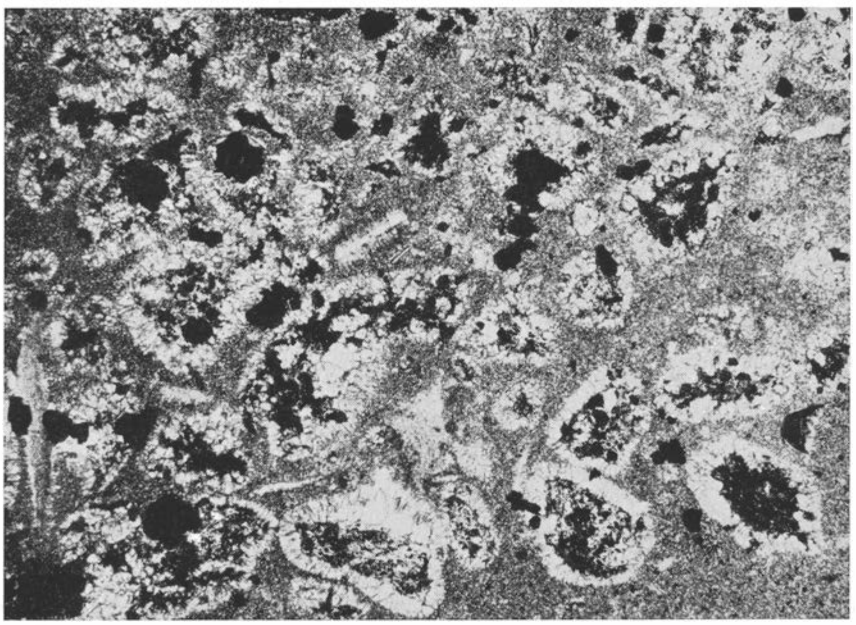

Fig. 80. Ceratopyge limestone. Matrix bituminous, microcrystalline, with pyrite and bituminous lumps surrounded by radiated calcite. Lower Ordovician. Flagabro, Skåne. (Prep. 6318, photo 1405.) — 20 ×.

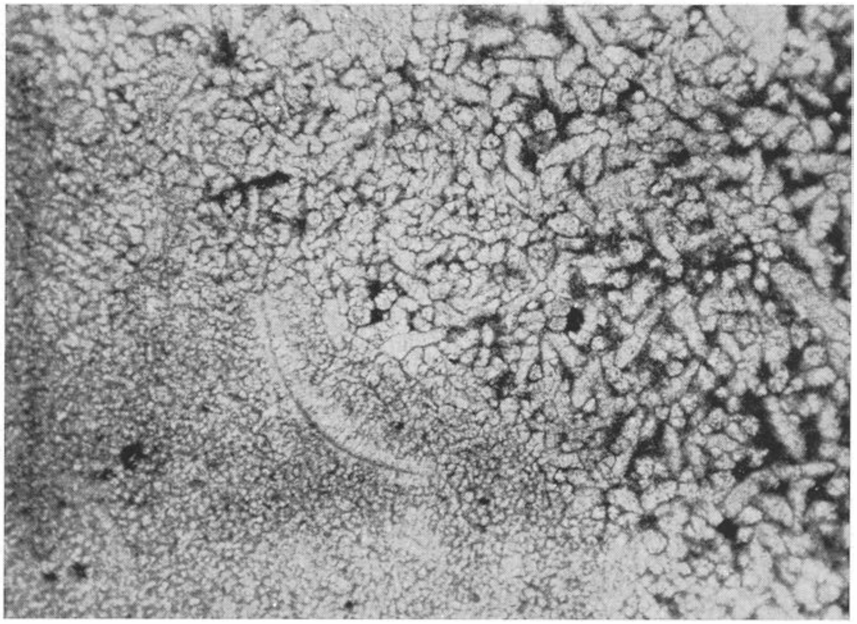

Fig. 81. Ceratopyge limestone. Granular aggregates of calcite, crystals partly spool-shaped. Matrix bituminous. Lower Ordovician. Flagabro, Skåne. (Prep. 6319, photo 1301.) — 60 ×.

metres' thickness, which in turn is covered by a flint-dense, brittle, light-grey fourth limestone bed.

Micro: Microcrystalline, even-grained with carapaces of trilobites (fig. 82). A few spicules of sponges have been observed, but not phosphorite or glauconite. Pyrite occurs only sparsely. This bed, too, probably belongs to the Ceratopyge series (cf. Fågelsång's Ceratopyge limestone p. 107).

In the drilling at Flagabro the Ceratopyge limestone was found at a depth of 32 m. A number of samples of it have been examined. They exhibit the same qualities on the whole as the beds described above, but certain details have not been observed previously and merit mention.

The lower bed is conglomeratic with one-centimetre-diameter pebbles in a finely crystalline, even-grained ground-mass with fairly abundant shell fragments and a few small grains of glauconite. The pebbles consist of fine-grained calcite interlarded with grains of glauconite and phosphorite. The pebbles obviouly originate from an older bed which was (partly) consolidated and disintegrated before it was definitively covered by new sediments. The second bed in the drill-core is dark-grey. The rock is crystalline-granular throughout with brown mud between the calcite crystals. Small phosphatic shells and somewhat larger calcareous fragments occur sparsely. The latter are completely recrystallized and surrounded by a calcite

Fig. 82. Ceratopyge limestone. Matrix microcrystalline, evengrained. Recrystallized fragments of trilobites. Lower Ordovician, Flagabro, Skåne. (Prep. 6320, photo 1302.) — 20×.

crust with radiated crystals. Glauconite appears fairly generally and in various forms: as rounded grains, as diffuse aggregates, and as a coating on phosphatic nodules. The glauconite is often pigmented on the surface. Metasomatic change to calcite is encountered in several places. Phosphorite is found in small, scattered lumps and diffuse masses, pyrite in small aggregates.

Summary and conclusions concerning the primary character, diagenesis, and formation of the Ceratopyge limestone at Flagabro.

The lowermost part of the Ceratopyge limestone at Flagabro in south-east Skåne has developed as a conglomeratic limestone or a limestone conglomerate with phosphorite. In the upper beds the phosphorite diminishes or disappears. Glauconite occurs abundantly in the lower beds, both authigenically and allothigenically. Pyrite is found in all the beds and is abundantly represented in the lower ones. Dark, bituminous mud forms a matrix between the remaining constituents. Fossils (calcareous and phosphatic fragments) occur only scantily.

The present texture of the rock can be entirely ascribed to diagenesis. The primary calcareous mud has crystallized into granular aggregates, and the dark, bituminous mud, deprived of its lime content, has come to form a matrix between the calcite crystals. The texture resulting from the diagenesis shows great variations, however, which must be ascribed to an irregular composition of the primarily deposited mud.

The highly calcareous sediment (which was deposited on the virtually lime-free bituminous mud which has formed the alum shale with *Dictyonema*) was primarily mingled with grains of glauconite and phosphatic nodules, also phosphorite with a crust of authigenic glauconite. In some places there were also pebbles of early consolidated parts of a similar calcareous sediment.

Rich in phosphorite and glauconite and partly conglomeratic, the lowermost beds of the Ceratopyge limestone of south-east Skåne are composed of two entirely separate groups of constituents: those belonging primarily to the limestone's original environment of formation, and those formed under other conditions. To the former group belong the phosphatic nodules and glauconite, to the latter the bituminous mud. This was originally deposited in calm, probably stagnant water. The deposition was interrupted when the water became more agitated. Thus arose the conditions which promoted the production of glauconite (see HADDING 1932) and caused this mineral to be formed in situ or to be deposited there after short transportation. Formation of phosphorite and enrichment of phosphatic nodules took place at the same time. Whilst this sedimentation in moving water was going on, no mud was deposited, but each reduction in the movement of the water brought a deposition of older suspended material and recently formed calcareous mud. Through changes in the movement of the water the different sediment fractions were mingled in the way the limestone now demonstrates.

During deposition of the upper beds the water was less agitated, the supply of bituminous alum-shale mud was negligible or nil, but the sedimentation of primary calcareous mud was greater. The conditions for formation and enrichment of phosphorite and glauconite had disappeared. The water was periodically relatively stagnant, as is evident from the interstratified mudstone beds. We have no reason to interpret the presence of these beds as a result of subsidence.

The great change in sedimentation does not occur where we draw the boundary between the Cambrian and Ordovician (between the Olenus shale and the Dictyonema shale) but during the formation of the phosphatic and glauconitic strata, which in south-east Skåne are situated in the upper part of the Ceratopyge series. Where in other areas we find corresponding strata resting directly upon Cambrian sediments, their deposition has taken place after and in connection with denudation of the earlier deposited Ordovician layers (e. g. Dictyonema sediments). This was clearly the case in northern Öland, probably in Västergötland, and possibly in Dalarna, where the basal bed of the Ceratopyge series, the Obolus conglomerate, contains fragments of earlier sediments of Ordovician age (HADDING 1927, p. 90).

Ceratopyge limestone, Fågelsång.

At Fågelsång, east of Lund, the Ceratopyge series is composed of alum shale (Dictyonema shale), above which is a series of limestone beds and strata of black

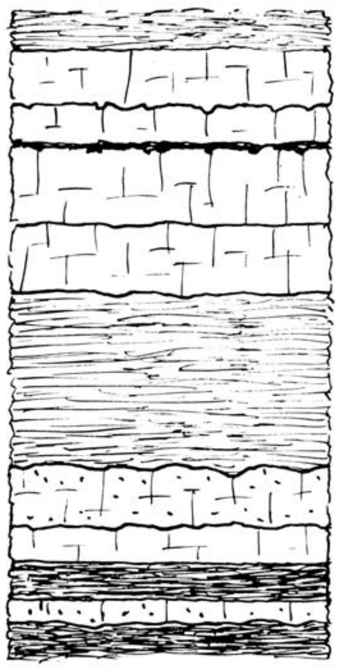

Fig. 83. Section through the Ceratopyge limestone at Fågelsång, Skåne. According to Hede 1951.

and grey shale. The limestone beds have a total thickness of barely 0,5 m. They are divided into two parts, a lower with three beds of 3, 5, and 8 cm respectively (see section, fig. 83), and an upper with four beds of 9, 10, 5, and 7 cm respectively. The lower beds are rich in grains of phosphorite and glauconite, the upper do not contain these minerals. As regards the character of the rocks, HEDE's description (1951, p. 28 ff.), which is based on the examination of a drill core, is here cited.

The three lowermost beds are of finely crystalline, dense, grey phosphorite-glauconite limestone with pyrite in small crystals and grains. The phosphorite grains are angular or round, mostly 0,5—3,0 mm (seldom more than 5 mm) in diameter. The glauconite grains vary in size from 0,2 to 2,5 mm. The shale between the lowermost beds is sharply and evenly delimited, but otherwise the strata are uneven and more or less corroded.

The four upper beds consist of dense, grey limestone, hard and with a splintery fracture reminiscent of chert. The two middle beds have strongly corroded upper surfaces. Like the lower banks they contain pyrite in the form of small crystals and grains.

A natural section of Ceratopyge limestone at Fågelsång was measured in 1893 by C. O. SEGERBERG and a report on the lithologic sequence was published in 1906 (MOBERG and SEGERBERG, 1906, p. 53 ff.). The thickness of the limestone is largely the same as that measured in the drill-core mentioned above. The localities are

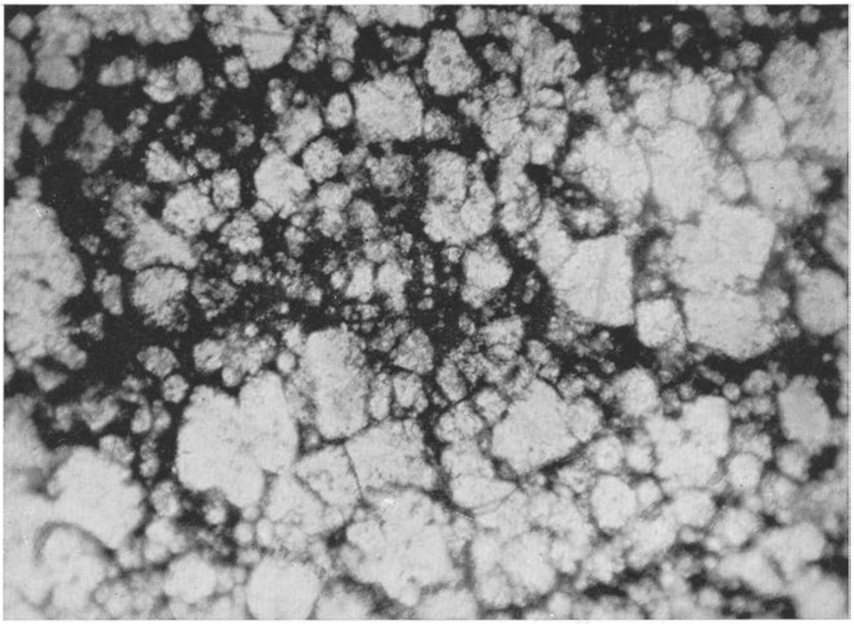

Fig. 84. Ceratopyge limestone. Calcite crystals in dark, silicified, argillaceous matrix. Lower Ordovician. Fågelsång, Skåne. (Prep. 6586, photo 1317.) — 60×.

situated only 600 m from one another. The rocks appear, however, partly different in the two places. The upper beds in SEGERBERG's section (as well as in the drill-core) are of a dense, grey limestone with splintery fracture. The pyrite of the section has been weathered away, and the limestone therefore exhibits a large number of cavities with rust-coloured walls. The lower beds of SEGERBERG's section (called the Shumardia limestone by MOBERG) are crystalline and blue-grey when unaltered, but when weathered they are dark rust-coloured and porous with a fine network surrounding the cavities from the dissolved calcite. The weathered rock has the typical structure of the spongy porous residue of chert (Backstein).

Micro: The unaltered Shumardia limestone has a mortar-like texture with irregular, angular crystals of calcite in a pigmented SiO_2-rich cement (fig. 84). Neither phosphorite nor glauconite has been observed in the rock, although it has undoubtedly contained these minerals primarily. The peculiar coarsely crystalline texture has not arisen through diagenetic processes alone. A dyke of dolerite traverses the section, and it is from contact with this that the limestone has got its secondary character.

The Ceratopyge limestone of Öland.

In the Öland series of strata there are several stratigraphical breaks in the Upper Cambrian and Lower Ordovician; in part they are represented by intraformational conglomerates (HADDING 1932, p. 11 ff.). The series is most complete in southern Öland, for example at Ottenby, where the Ceratopyge limestone, too, is best developed (see section, fig. 93, p. 123 and TJERNVIK 1956, p. 147).

The glauconitic limestones of the Ceratopyge series have been described and discussed in detail by the author in connection with an investigation of Sweden's glauconite sediments (HADDING 1932). They will not, therefore, be further considered here except insofar as they display different types of Ceratopyge limestone with little or no glauconite.

Ceratopyge limestone, Ottenby.

Macro: At Ottenby the Ceratopyge limestone is in beds of 5—10 centimetres. Macroscopically the rock is dense or fine-grained and grey with green-tinged, diffuse parts. Pyrite is visible in small aggregates, and glauconite occurs partly as scattered grains at the boundary with the glauconitic shale, partly as impregnation and coating on corrosion-surfaces. The limestone is fairly rich in fossils, *Ceratopyge forficula*, *Euloma ornatus*, *Niobe insignis*, etc. (see TJERNVIK 1956, p. 146).

Micro: Microcrystalline ground-mass, granular (3—8 μ) with small, thin fragments in abundance (approx. 0,1 mm), scattered larger fragments of trilobites and brachiopods (1—8 mm). Pyrite in cubes and globular aggregates scattered throughout the rock but enriched in thin layers. Glauconite partly in the form of well-defined grains (allothigenic) rounded or torn by secondary calcite crystals, partly as diffuse lumps and coating (authigenic), the latter on uneven corrosion-surfaces. The matrix between the calcite grains is a greyish-yellow cryptocrystalline substance, double-refracting. It is of the same nature as the bituminous material in the alum shale. In the fine-grained limestones it is easily overlooked, in the more coarse-grained it is accumulated between the calcite crystals.[1]

Diagenesis: Complete recrystallization of the calcareous mud during formation of granular texture. The fossil fragments are partly unchanged, partly recrystallized. Grains of glauconite not infrequently have secondarily formed crystals of siderite or calcite. Pyrite in the form of single crystals or small aggregates.

Primary character and formation: The Ceratopyge series of Öland is a purely marine formation. Where the sequence of strata is most complete, its oldest part is made up of alum shale, which lithologically forms a direct continuation of the Olenus shale of the uppermost Cambrian. The lithologic change occurs when the alum

[1] The glauconitic limestones of the oldest Ordovician in Öland are partly grey, partly coloured violet, red, brown, or yellow, as well as green (from glauconite). The grey types have a matrix which conforms exactly with that described above for the non-glauconitic limestones. Only the grain size is more varied. The more deeply coloured types exhibit the same variations as the Planilimbata limestone and will be dealt with in connection with this. Actually it is difficult to find in the rocks a definite limit between the Ceratopyge series and the Asaphus series, where the boundary layers, as in southern Öland, are a series of limestone beds without either faunistically or lithologically marked changes.

shale is overlain by glauconitic sand. The calm, strongly reducing environment in which the alum shale with its high bitumen content was formed changed to an environment with probably less deep and certainly more open water. When the formation of limestone began, however, a change in the mobility of the water occurred; grains of glauconite were enriched and deposited together with calcareous mud. With a richer deposition of calcareous material a change in the degree of acidity of the water began. The p_H value rose, and the weakly reducing environment became neutral or slightly oxidizing. The increased supply of oxygen in the bottom mud brought a flourishing of the benthogenic fauna: trilobites, brachiopods, etc. Occasional fluctuations occurred, which can be traced in the corrosion of the limestone beds and the deposition of glauconitic mud on the corrosion-surfaces.

From the character of the rocks and lithologic sequence we can infer an alternating deposition and dissolving of calcium carbonate; we can also judge the causes of this alternation, but it remains to find out the way in which the calcareous mud was formed. In the most slightly crystallized Ceratopyge limestones (the densest) the diagenetic calcite crystals are intermingled with extremely small fossil fragments. The calcareous mud has thus primarily contained finely crushed fossils (microcoquina). The recrystallized larger part of the limestone must, however, have been composed primarily of extremely fine-grained calcareous mud, the character of which we cannot infer from a study of the rock. Did the deposition of calcium carbonate occur as a direct consequence of the change in the p_H value of the water, or did it occur indirectly through a flourishing of micro-organisms caused by the same change? The same question must be put concerning the formation of other limestones of similar character.

The Ceratopyge limestone of Västergötland.

In the central Swedish Cambro-Silurian areas of Västergötland, Östergötland, and Närke the Cambrian alum shales are overlain in certain areas by glauconitic limestones belonging to the Ceratopyge series. Occasionally, however, Ordovician alum shale (Dictyonema shale) is found between the Cambrian and the Ceratopyge limestone (Kleva, Knivinge, etc.). The Ceratopyge series is represented in certain areas by only a thin glauconitic sediment; it may even be entirely absent, in which case the Asaphus series (the Planilimbata limestone) rests on the Upper Cambrian sediments. A few examples will be given below of typical or unusual forms of limestone of the Ceratopyge series of the above-mentioned central Swedish areas. For additional information reference should be made to the detailed sections published by WESTERGÅRD (1922), THORSLUND (1937), and TJERNVIK (1956).

Ceratopyge limestone, Mossebo, Hunneberg.

The limestone which at Mossebo lies between the Upper Cambrian (the Peltura zone) and the shale with *Tetragraptus phyllograptoides* was measured in 1892 by

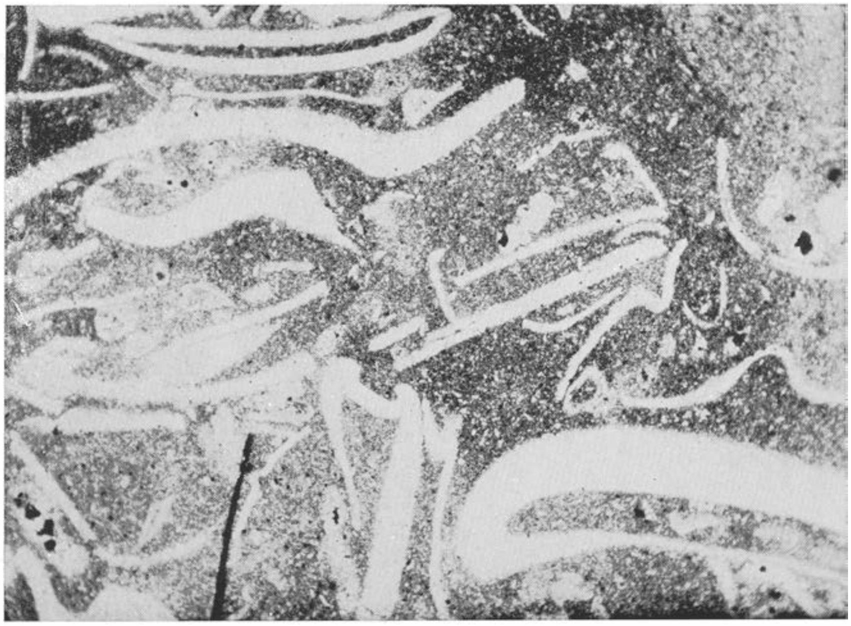

Fig. 85. Ceratopyge limestone. Carapaces of trilobites in matrix of minute fragments and calcite crystals. Lower Ordovician. Mossebo, Västergötland. (Prep. 8820a, photo 1604.) — 20×.

MOBERG and VON SCHMALENSEE and found to be 2,9 m (MOBERG and SEGERBERG 1906, p. 45). They regarded the whole limestone series as belonging to the Ceratopyge series. In the section described by TJERNVIK (1956, p. 118) the limestone has a thickness of 1,3 m, and only the lowermost part, 0,4 m, belongs to the Ceratopyge strata (see section, fig. 106, p. 140). The upper and larger part of the limestone series belongs, according to TJERNVIK, to the Asaphus series (Arenig: the zone with *Plesiomegalaspis armata* 0,4 m and the zone with *Plesiomegalaspis planilimbata* 0,5 m). The series consists of dark, almost black limestones; only the uppermost beds (0,1 m) are lighter grey.

The lowermost bed of the Ceratopyge limestone has been investigated.

Macro: The bed consists of a lower part with relatively coarsely crystalline calcite in a black matrix, a middle part with particularly abundant trilobite fragments, and a black, dense upper part. Pyrite is found in the middle part. There is no glauconite. The bed is about 5 cm thick.

Micro: The lower part consists of a calcite aggregate with isometric crystals (0,5—1 mm) and intermingled flocks of black pigment (containing bitumen). No fossil fragments have been observed in the highly recrystallized mass (fig. 2, p. 11).

The very fossiliferous middle part contains, in addition to whole carapaces of trilobites (inc. *Triarthrus angelini*), an accumulation of fragments (1—5 mm). The matrix consists of completely crystallized minute fragments (25—60 μ) and isometric grains of calcite (5 μ). Pigment is present in varying quantity (fig. 85).

The upper, dense part consists of recrystallized fossil debris of the same size as in the matrix of the very fossiliferous middle part. Pigment is more abundant than in the lower parts of the bed. Fragments of trilobites are few and small.

Diagenesis: The bed displays throughout clear recrystallization. The development of the larger grains of calcite in the lower part is notable.

Formation: Deposition of calcareous mud in not very open water of medium depth. Decreasing bitumen content and somewhat increasing content of argillaceous mud can be traced, and the mass appearance of trilobites in the middle part of the bed is of interest for determination of the fluctuations in the environment of formation. Worthy of note is the fact that the pyrite content is greatest in the richly fossiliferous layer.

In Östergötland the Ceratopyge limestone is less well developed than in Västergötland, and in Närke there is generally a break in the series of strata comprising the whole Ceratopyge series. The unimportant rocks representing the series in these provinces are of no special interest for the outlines given here.

The Ceratopyge limestone of Dalarna.[1]

In Dalarna, where there is no Cambrian at all, the Ceratopyge series rests directly upon pre-Cambrian rocks. The sequence of strata begins with a conglomerate and sandstone, which is overlain by glauconitic sand and glauconitic limestone (cf. HEDSTRÖM 1896 and HADDING 1927, p. 88 and 1932, p. 75). The limestone is of the same nature as that found in other provinces. Its only peculiarity is that it contains a varying quantity of fragments of felspar and quartz from the weathered Archean rocks on which the series was deposited.

As was mentioned, the deposition of calcareous sediments in Dalarna during the earliest Ordovician did not begin with the formation of the glauconitic limestone. The basal conglomerate — the Obolus conglomerate — primarily contains calcium carbonate, locally in such abundance that the rock can be regarded as a limestone with intercalated fragments of dense limestone and phosphorite, glauconite grains, brachiopod shells, splinters of granite, etc. (fig. 86). Some of the rock fragments and the thick shells are distinctly rounded. They were worn down before they became embedded in the calcareous mud. The rock is an example of how fluctuating conditions of sedimentation can result in beds with a mixture of mud and coarse grains.

For the sequence of strata and fossil content of the Lower Ordovician of Dalarna see TJERNVIK 1956, pp. 164—168.

[1] TJERNVIK (1956, p. 85) puts this limestone in the Asaphus series, in opposition to WIMAN 1906, WARBURG 1910, MOBERG 1911.

Fig. 86. Glauconitic limestone. Matrix of coarse-crystalline calcite, grains of glauconite (black) and phosphorite, splinters of granite. Lower Ordovician. Sjurberg, Dalarna. (Prep. 7548, photo 1359.) — 20×.

Asaphus series, Arenigian. Orthoceras limestone.[1]

The limestones belonging to the Asaphus series of the Lower Ordovician have long gone under the common designation Orthoceras limestone. The stratigraphical compass of the latter is different in different parts of Sweden: in certain areas, for example in Öland, the Orthoceras limestone comprises the whole of the Asaphus series, in others, for example in Skåne, limestones occupy only a small part of the series, which otherwise contains shales. By and large, however, the Orthoceras limestone is the thickest and most wide-spread of the Ordovician limestone series.

A common feature of the different zones of the Orthoceras limestone is distinct bedding and very persistent strata. The beds are separated by thin layers of marl, and colour banding may be present in them. The bedding planes are mostly uneven, often obvious corrosion planes. Large fossils are relatively rarely found in well-preserved condition, but trilobites and cephalopods (inc. *Orthoceras*), however, are everywhere characteristic of the series of strata. Smaller fragments of these fossils

[1] See Störmer 1953, pp. 44—45, Jaanusson and Mutvei 1953, p. 7, note 1, and Jaanusson-Strachan 1954, p. 684.

and others appear abundantly, in many of the beds to such an extent that they form almost the whole rock. The Orthoceras limestone is a typical fragment limestone, a detrital or clastic limestone, calcarenite or calcilutite.

To give an idea of the changes in sedimentation the different stratigraphical zones of the Asaphus series will be dealt with separately, first of all for the area, Öland, where the limestone is best developed. The corresponding limestones of the remaining areas will be described and discussed in a similar way. In addition the reader is referred to the diagrams of the development of the Orthoceras limestone in the different areas with typical limestone facies and with mingled shale and limestone facies (see also scheme p. 100).

The Orthoceras limestone of Öland.

"Probably nowhere in our country does the Orthoceras limestone occupy such a large continuous area, and probably nowhere is it so readily accessible, as in Öland" wrote MOBERG when he had completed his investigation of the stratigraphy of the Ölandian limestone (MOBERG 1890, p. 11). MOBERG's supposition has proved correct, and the island still has many problems to offer to anyone interested in the stratigraphical, paleontological, or lithological conditions of Orthoceras limestone. Several investigators have carried out and published more or less comprehensive surveys of the Orthoceras limestone of Öland.[1] Geological surveying and mapping were carried out largely by J. C. MOBERG in southern and central Öland and by G. HOLM in the northern part of the island. The result of their work has been partially published by C. WIMAN (WIMAN 1902 a—b, 1904, and 1906 a).

The Ordovician strata of Öland are extensive (the island is about 120 km long), and sedimentation was therefore not uniform over the whole area at any time during the formation of Orthoceras limestone. The variations are, however, surprisingly small and of no general lithological importance. The following account of the rocks therefore pays less attention to local variations than to the features which are common to the sediments in each separate zone. The changes which sedimentation undergoes as zone is added to zone can be traced outside Öland, too, and they must have been caused by regionally active forces. The changes in lithological character are not, however, abrupt, and the different zones are not sharply delimited. In making his stratigraphical scheme of the Orthoceras limestone of Öland, therefore, MOBERG (1890, p. 18 etc.) introduced "transition beds" between certain zones where the boundaries were particularly difficult to draw. MOBERG's division of the series of strata, which will largely be followed below, is apparent from the attached scheme, which also shows old and recent suggestions for terms.

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[1] HOLM 1882, J. G. ANDERSSON 1895, MOBERG 1904 and 1911, NÖRREGAARD 1908, REGNÉLL 1940, 1942, and 1948, BOHLIN 1949 and 1955, JAANUSSON 1955, TJERNVIK 1956.

Orthoceras limestone of Öland.

Linnarsson 1876[1]	Moberg 1910 S. Öland	Bohlin 1955 N. Öland
Upper grey limestone	Centaurus limestone[2] (Transition beds)	Schroeteri limestone[3]
Upper red limestone	Platyurus limestone Gigas limestone (Transition beds)	Platyurus limestone Gigas limestone
Lower grey limestone	Upper Asaphus limestone (Sphaeronite bed) Lower Asaphus limestone	Raniceps limestone Expansus limestone Lepidurus limestone
Lower red limestone	Limbata limestone Planilimbata limestone	Limbata limestone Upper Planilimbata l. Lower planilimbata l.

Planilimbata limestone of Öland.

Between the typical, paleontologically well-defined Ceratopyge limestone and the typical Planilimbata limestone lies a series of glauconitic beds. The lower of these are counted as belonging to the Ceratopyge series, the upper to the Planilimbata zone. Where the boundary ought to lie is a difficult matter to decide paleontologically, and from a lithological point of view it is unimportant. The fluctuations between beds with abundant glauconite and beds with little glauconite recur throughout the series, not rhythmically or otherwise regularly, but similarly. The calcareous mud contains more or less iron hydroxide, argillaceous, and organic material owing to changes of the environment of sedimentation, independently of at what time it was formed. The above-mentioned glauconitic strata are dense and light-grey in one place, coarsely crystalline, dark-green and reddish-brown in another. Between these extremes there are all the intermediate types.

The Planilimbata limestone (in contrast to the Ceratopyge limestone) is well developed in central as well as in southern Öland. Some examples of the character of the limestone will be given.

The Planilimbata limestone is exposed in the cliff ("Landborgen") east of South Möckleby, and it is quarried there in several places. A continuous section through this limestone and the adjacent strata above and below has been measured in detail by Moberg and von Schmalensee at Gettlinge.

[1] Linnarsson manus. according to Nathorst 1881, p. 593.

[2] Also called Chiron or Schroeteri limestone after *Illaenus schroeteri* Schlotheim 1823, $=$ *I. centaurus* Angelin 1853/54 $=$ *I. chiron* Holm 1883.

[3] According to Bohlin Middle Ordovician, Chasmops series.

In 1928 in a then newly opened quarry at Perstorp, 2 km north of South Möckleby, beds of Planilimbata and Limbata limestone were observed. The Planilimbata limestone showed the development normal in southern Öland, with lower beds rich in glauconite and upper beds poor in or almost completely free of glauconite. Apart from the possible glauconite content the limestone is dense or finely crystalline, light grey with a faint tinge of violet. The upper bedding plane is generally slightly corroded and coated with a thin crust of authigenic glauconite. Fossil fragments are scanty as a rule but are accumulated in certain parts. Like the glauconite grains, they are distributed in the rock in a way that shows that changes in the sedimentation conditions have taken place on repeated occasions, even during the formation of a bed (see fig. 87).[1]

In the limestone quarry at Degerhamn, south of South Möckleby, is found more or less the same series of strata as at Perstorp.

From the Planilimbata limestone of *southern Öland* three macroscopically different types are more closely examined.

1. *Dense, grey limestone.*

Quarry at Perstorp, bed 10 cm thick.

Macro: Dense with granular parts, light-grey with a tinge of violet. Scattered small grains of dark-green glauconite. Upper bedding plane slightly corroded and with a thin crust of authigenic glauconite. Fossil fragments unevenly distributed, in certain parts greatly accumulated, in others rare.

Micro: Matrix microcrystalline, even-grained (grains 0,01 mm), with varying content of fossil fragments (0,05—1,0 mm). Pyrite in scattered cubes, 0,1—0,3 mm (fig. 88).

2. *Crystalline, mottled, glauconitic limestone.*

The south limestone quarry at Degerhamn. Bed in glauconitic shale.

Macro: Crystalline with dark-green glauconite grains in white calcite (fig. 89). Bedding plane with glauconite crust and pyrite concretions of 10 mm diameter.

Micro: Coarse with 1—6 mm-large crystals of calcite, faintly pigmented with small argillaceous flakes but with no matrix between the crystals (fig. 90). The glauconite grains, 0,1—1,5 mm, are partly replaced by calcite. No fossil fragments have been preserved.

[1] A relatively small change in the movement of the water has increased or diminished its ability to transport and deposit coarser or finer material, and even an occasional turbulent motion in the water can have caused unevenness in a mud during deposition. The Planilimbata limestone dealt with here, like many others, has acquired its uneven structure through short-lived and locally varying changes in the movement of the water.

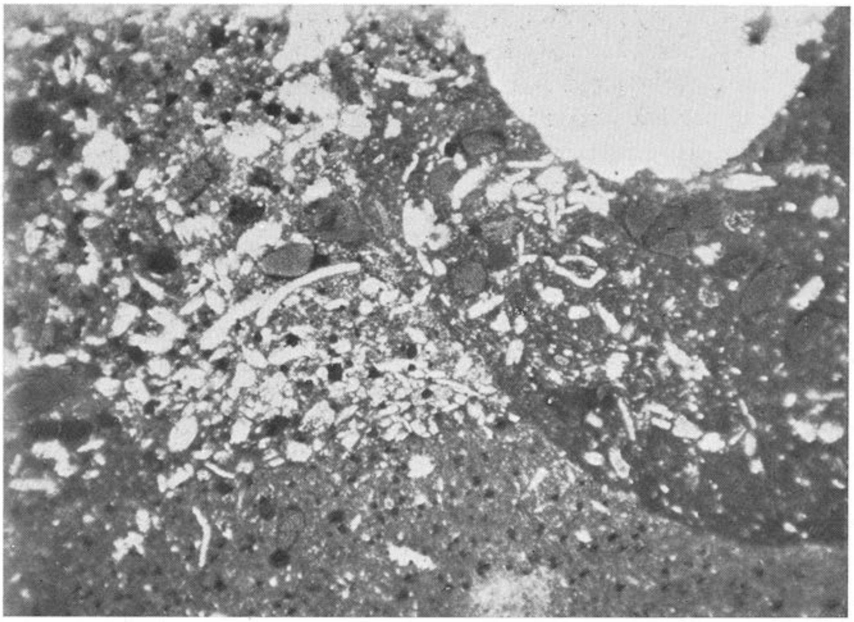

Fig. 87. Planilimbata limestone with corrosion surfaces. Upper part with glauconite grains, middle part crammed with fragments, lower part dense. Lower Ordovician. South Möckleby, Öland. (Prep. 3249, photo 1634.) — 20×.

Fig. 88. Fragment limestone. Matrix microcrystalline. Stratification disturbed. Planilimbata limestone, Lower Ordovician. Perstorp, Öland. (Prep. 3250, photo 1637.) — 20×.

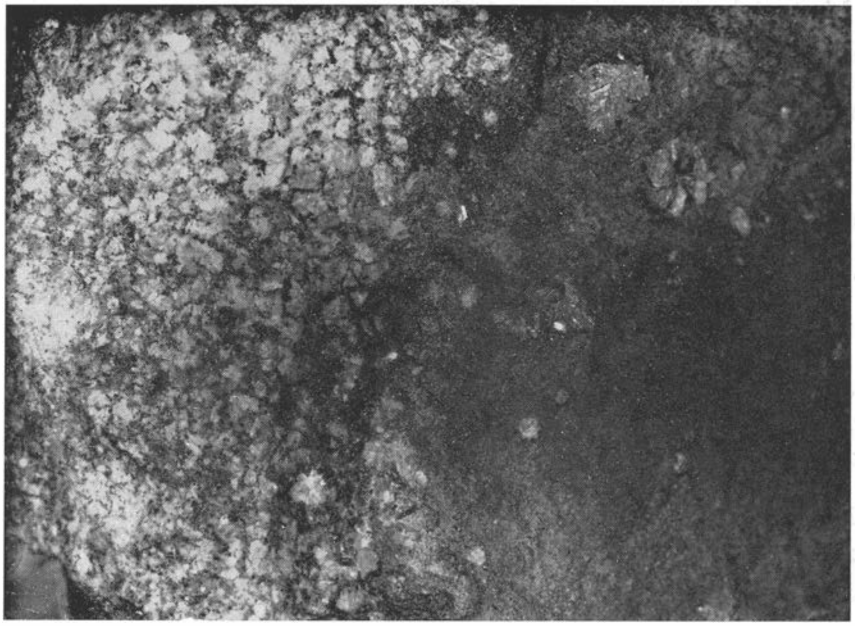

Fig. 89. Glauconitic limestone. Bedding surface with glauconite sand and pyrite (right half of the fig.) on coarse-grained calcite with glauconite. Planilimbata limestone, Lower Ordovician. Degerhamn, Öland. (Photo 1790.) — $^1/_1$.

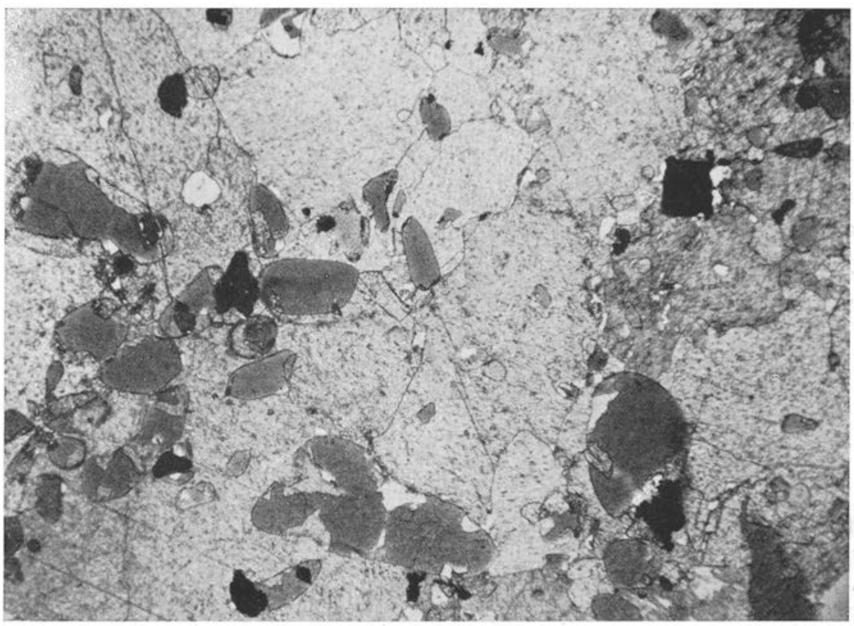

Fig. 90. Glauconitic limestone. Coarse-grained calcite with grains of glauconite, partly replaced by calcite. Planilimbata limestone, Lower Ordovician. Degerhamn, Öland. (Prep. 6524, photo 1789.) — 30×.

3. *Crystalline, dark reddish-brown and green, glauconitic limestone.*

Mysinge hög, east of Mörbylånga.

Macro: Middle part of the bed finely crystalline, grading into more coarsely crystalline towards the bedding planes. The colour is dark reddish-brown tinged with varying amount of grass-green. Abundant glauconite grains.

Micro: Well-crystallized calcite, which is frayed in contact with the dense, red (hematite-coloured) interstitial mass (fig. 91). The glauconite grains are reniform, cracked, and partially replaced by calcite.

The development of Planilimbata limestone in *central Öland* can be studied at Köping, north of Borgholm. Several sections have been measured there and examined by G. Regnéll (1942), and one of them (sect. 4) will be given here.

10a	Red limestone	1.25	Limbata limestone
10b	Variegated limestone: red, yellow, green		
9	Bluish-grey shale, locally pinching out	0.07	Planilimbata limestone
8	Variegated limestone: red, yellow, green	0.60	
7	Pale green and light violet, dense limestone containing grains of glauconite	0.10—0.15	
6	Glauconitic sand, soft, clayey	0.15	Ceratopyge series
5	Coarse-crystalline limestone, in fresh break mottled: white, yellow, green; on weathered surface red	0.40—0.50	
4	Violet and greyish-green, dense limestone. In the lower part glauconite	0.20	
3	Glauconitic shale with clayey layers	1.75	
2	Hard shale, filling the inequalities of the upper surface of the substratum	0.08	
1	Dense, greyish-black limestone	0.45+	Cambrian

The variegated limestones in beds 8 and 10 have a more or less similar development, and the rock described below can be taken as the type for the Planilimbata zone of central Öland.

Planilimbata limestone, Köpings klint.

Macro: Bed 0,1 m thick. Bedding planes uneven, coated with glauconite. Lower part of the bed dense, greyish-violet or brownish-violet with scattered small grains of glauconite. Upper part of the bed crystalline, variegated, with bright grass-green and pure brownish-red parts alternating with multicoloured. Relatively large glauconite grains form about 50 % of the sediment in this part of the bed. A middle

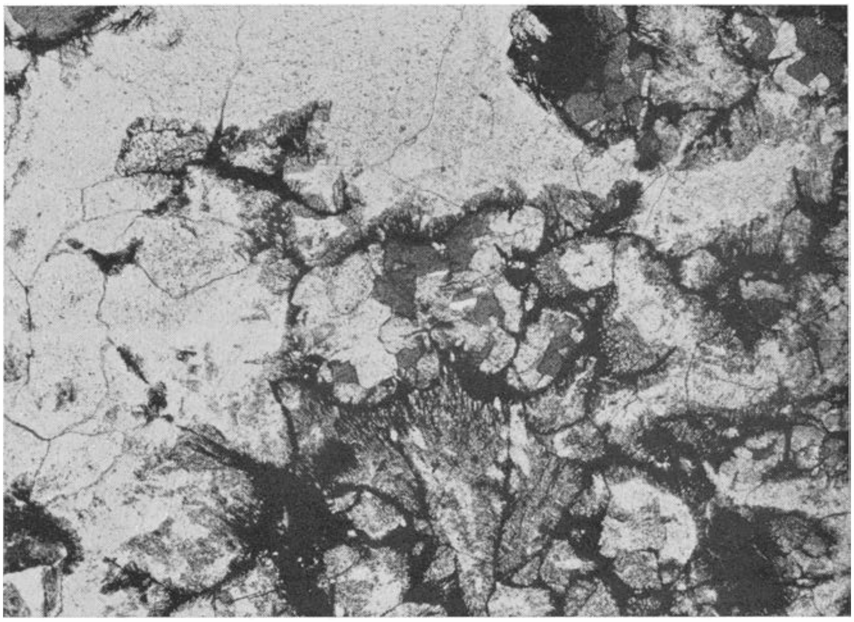

Fig. 91. Glauconitic limestone, hematite-pigmented, coarse-crystalline. Planilimbata limestone, Lower Ordovician. Mysinge hög. (Prep. 7140, photo 1400.) — 20 ×.

part containing one or more light brownish-yellow, ochre-coloured bands has a diffuse lower boundary with the dense limestone but often a sharp boundary with the richly glauconitic upper part.

Micro: Lower part (prep. 3026). The macroscopically dense limestone is microscopically crystalline-granular with isometric or rod-shaped calcite crystals, 0,05—0,15 mm. Between the crystals there are scattered flakes of hematite, approx. 0,001 mm. Thin fragments, coated with radiated calcite crystals, occur here and there. Glauconite in scattered small grains $<0{,}5$ mm.

Upper part. The crystalline calcite mass, with grains 0,2—2 mm, is irregularly interlarded with green grains of glauconite and red hematite pigment. The macroscopically grass-green parts have the glauconite grains packed in a calcite which is only faintly pigmented (fig. 92). The reddish-brown parts have abundant hematite grains, 0,003 mm, and submicroscopic hematite dust. The fossil fragments are small and strongly corroded.

The yellow bands are found both in the dense part with little glauconite and in the coarse part with abundant glauconite, and it is only the pigment which distinguishes the different-coloured parts from each other. In the yellow bands the small grains and flakes of hematite are completely missing. The pigment consists of a colloidal, yellow substance, probably ferric hydroxide.

Certain variations in the development of the limestone deserve special mention. Not infrequently it is found that the borders between the different-coloured parts

Fig. 92. Variegated limestone: lower left part yellow, fine-grained, upper right part green, glauconitic, coarse-grained. Middle part red, hematite-pigmented. Planilimbata limestone, Lower Ordovician. Köping, Öland. (Prep. 6922, photo 1328.) — 60 ×.

are obliterated or hazy and irregular. Only a disturbance of the already formed different-coloured bands, e. g. by wave action or sliding, can have given rise to these irregularities. They appear above all in parts with coarse grains of glauconite, thus in sediments which have been deposited in agitated water (cf. HADDING 1932).

In several beds the yellow band is delimited on the upper side by a clear corrosion-surface with a crust of authigenic glauconite. Deep grooves and pits are clearly noticeable in this surface. The dense, corroded limestone must have consolidated before the yellow pigment and glauconite crust were formed. The grooves and pits are generally filled with coarse-grained, allochthonous glauconite.

Towards the *northern part of Öland* the Planilimbata limestone diminishes in thickness, but the rock has largely the same development there as to the south. Variegated, red-yellow-green beds, more or less glauconitic and with marked corrosion-surfaces, are encountered in several places at the base of the Asaphus series both in the north and to the south. The traces of rearrangement or denudation are more distinct, however, in the north, and they may there indicate the occurrence of locally developed conglomerates.

How varying the Planilimbata limestone of Öland is with regard to thickness and character is demonstrated in the adjoining fig. 93. The three schematic sections are

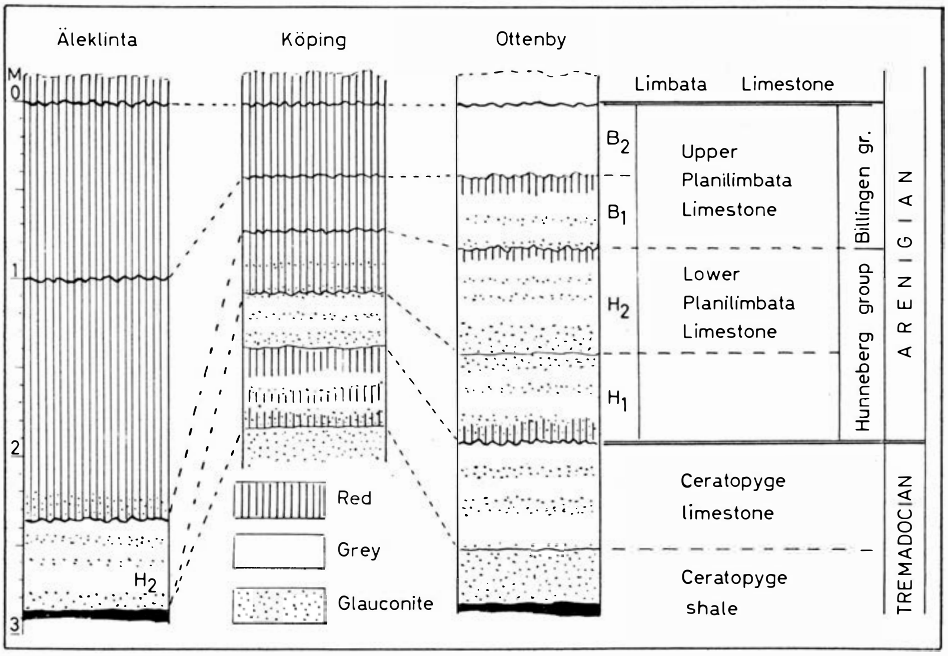

Fig. 93. Sections through the Ceratopyge and Planilimbata limestone of Öland (acc. to TJERNVIK 1956).

based on TJERNVIK's report, published in 1956, of his detailed and carefully executed investigation of the early Ordovician of Sweden, which is principally a stratigraphical division of the series of strata based on faunistic investigations, but which also contains numerous and illuminating details about the rocks. As can be seen from the sections, the series of strata is less complete at Äleklinta (the northernmost of the three sections) than at Ottenby and Köping. In northern Öland the break is even greater. There the lower Planilimbata limestone may contain strongly corroded, partly conglomeratic beds (as at the boathouses at Bruddestad) or be completely absent (as at Böda harbour).[1]

The colour-banding of the beds and the corrosion-surfaces often connected with it, will be illustrated by the following example from the boathouses of Bruddestad.

[1] On the Planilimbata limestone in the drill-core from Böda harbour JAANUSSON writes (1955, 165): "Deposition of the Upper '*Planilimbata*' limestone on the eroded surface of the *Ceratopyge* shale began with an accumulation of glauconite sand, consisting mainly of rounded or tabular allochthonous grains and including relatively large quartz grains and phosphorite nodules ... The *Ceratopyge* limestone and the Lower '*Planilimbata*' limestone (of TJERNVIK 1952), well developed e.g. in southernmost Öland, are missing at Böda hamn, and the above-mentioned boundary thus denotes a considerable hiatus. The distribution of iron, phosphorus, and calcareous substances as well as of glauconite etc. in the layers on both sides of the boundary has been described and discussed by HESSLAND (1955, 'Transitional layers', pp. 73—75, 88—89)."

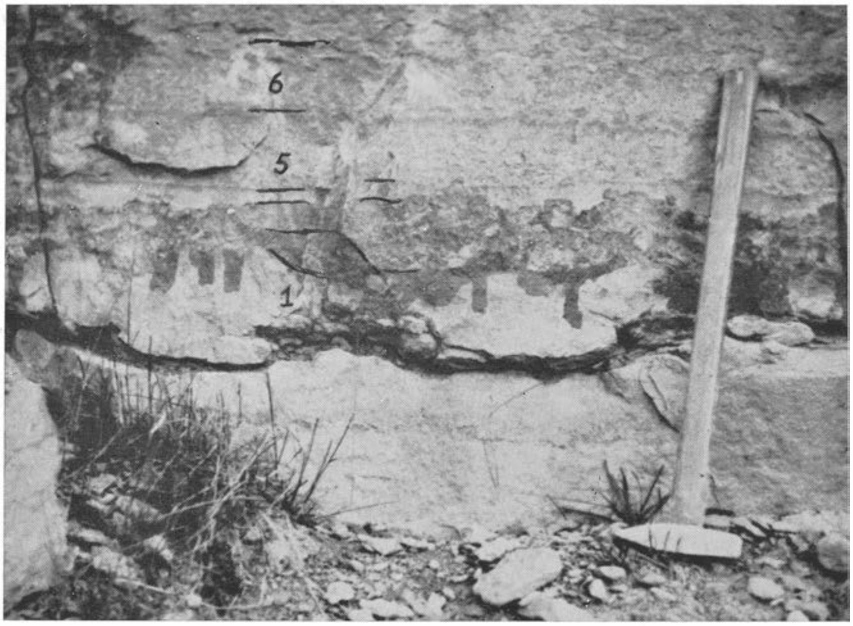

Fig. 94. Natural section through the Planilimbata limestone at Bruddestad, Öland.

Planilimbata limestone, Bruddestad.

At the boathouses of Bruddestad, south of Djupvik, a limestone bed was observed in the uppermost part of the Planilimbata zone with no less than seven layers, separated by corrosion-surfaces or distinct change in the sediment mass (fig. 94). The bed has the following composition:

7	(uppermost) Dense, greenish-grey with *M. planilimbata*	2 cm
6	Dense, greenish-grey with glauconite coating	4 ”
5	Dense, violet-grey, at top with glauconite coating on yellow band	5 ”
4	Dense, greyish-green, at top with glauconite coating on yellow band. Even surface	1—2 ”
3	Dense, yellowish-grey with pebbles of dark glauconitic sand. Corroded surface with glauconite coating on yellow band	2—3 ”
2	Coarse, dark, glauconitic sand with pebbles of dense, grey limestone. Conglomeratic. Indistinctly delimited towards the hanging wall	1—5 ”
1	Dense, grey limestone, strongly corroded surface without glauconite coating or yellow colouring	0—4 ”

Despite distinct corrosion-surfaces with glauconite coating the union is good between the different parts of the limestone bed. Worthy of note is the fact that consolidation of the deposited mud occurred so rapidly that fragments of one stratum could be torn loose and form part, as pebbles, of the overlying stratum, and that the pebbles can consist of glauconitic sand (pebbles in stratum 3) as well as of dense limestone (pebbles in stratum 2). We have no reason to assume a large hiatus in the series of strata where these conglomerate formations occur, even if the series is incomplete in other respects (see HADDING 1932, p. 12 etc.). At Horns udde 25 km north of Djupvik, the breaks are larger and the conglomerates better developed, but even here there is Planilimbata limestone with normal development, both dense, uniform greyish-green, and variegated with green, yellow, and red bands (see HADDING 1932, p. 36 et seq.).

The fossil-content of most of the beds is negligible. The fragments are small and thin, and they never occupy an appreciable part of the rock. On certain bedding planes, however, they may be accumulated.

Pyrite occurs sparsely in the Planilimbata limestone. Only in isolated instances have large concretions been encountered.

Summary and conclusions concerning the Planilimbata limestone of Öland.

The characteristic features of the Planilimbata limestone of Öland are the following: abundance of glauconite, poverty of fossils, strong colour-banding.

The glauconite appears sometimes allothigenically — often in coarse grains, sometimes authigenically — especially on corroded bedding planes. In the dense, light greyish-green limestone beds glauconite is found in finely-divided form.

Fossils are not absent in the Planilimbata limestone, but they are less common than in other parts of the Asaphus series. Especially remarkable is the fact that the numerous fragments are strongly corroded and recrystallized (fig. 95). They are best preserved in the dense limestones. The fragments which were present primarily in the now crystalline limestone have been more or less obliterated during diagenesis.

The uniformly coloured beds are light-grey, greyish-green, or greyish-violet. The strong colours like red, reddish-brown, yellow, and grass-green are common as bands in the beds. The green colour always originates from glauconite, the red from hematite dust. The causes of colour-banding will be discussed in another context.

The bedding of the Planilimbata limestone is distinct, but the beds consist not infrequently of several connected sections. In the upper parts of the Asaphus series the limestone cleaves into thin slabs along thin layers of a loose substance, usually marl mixed with hematite dust. Between the beds of the Planilimbata zone there is often glauconitic sand. Corrosion-surfaces with glauconite coating may be found inside the thicker beds.

The microtexture of the limestone, finely or coarsely crystalline, has arisen during diagenesis. It is a striking fact that the occurrence of firm, allochthonous glauconite grains has furthered the formation of the more coarsely crystalline forms.

Formation: The Planilimbata limestone of Öland has been deposited as calcareous mud with abundant finely-divided fossil fragments but with no large quantity of

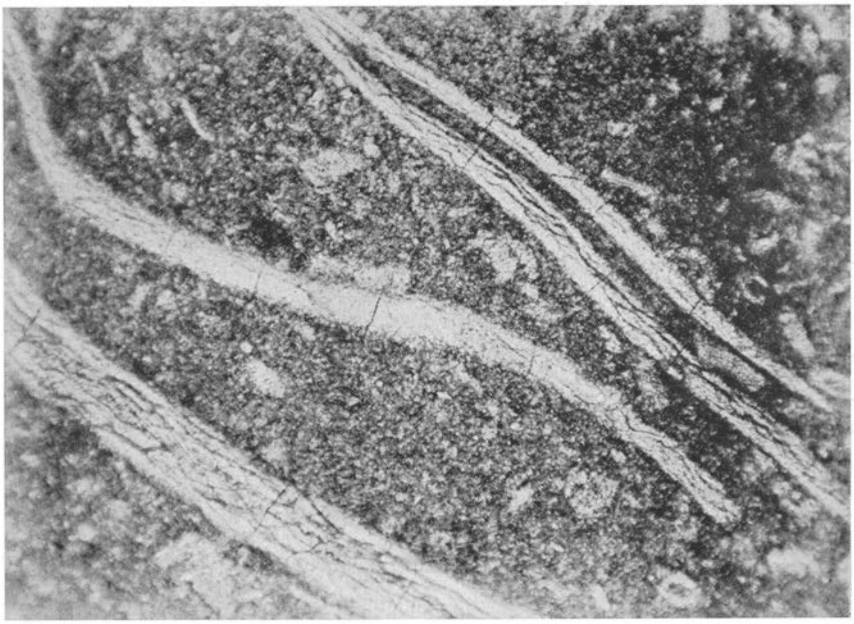

Fig. 95. Planilimbata limestone. Matrix of fine-grained fragments and microcrystalline calcite. Carapaces of trilobite corroded and recrystallized. Lower Ordovician. Bruddestad, Öland. (Prep. 6617, photo 1327.) — 60×.

coarser fragments. The presence of allothigenic, coarse grains of glauconite shows that time and again currents have influenced sedimentation. They have also had a corroding effect and contributed to a coating of glauconite on the corrosion-surfaces. The calcareous mud has been deposited in a neutral or reducing environment, only locally and exceptionally in an oxidizing. Deposition has taken place in shallow water, but no trace can be found of its having occurred in or immediately below the littoral zone. The variations in the lithologic character (material, colour-banding, conglomerate-formation) have arisen, however, during a general shallowing of the sedimentation area.

Limbata limestone in Öland.

The Limbata limestone of Öland is well exposed on the west coast. The upper part of the cliff ("landborg") in the southern part of the island consists of this limestone. It is quarried in many places, especially where it consists of firm, uniformly thick beds of 6—10 cm. These are shipped out on a large scale and are used as floor and paving flags.

The Limbata limestone is of remarkably even thickness, about 3 m, throughout the whole island. Its lithologic character shows no great variations, but the colour is varied, even if the red, brown, and dark-greyish-violet (reddish-grey) nuances are particularly characteristic.

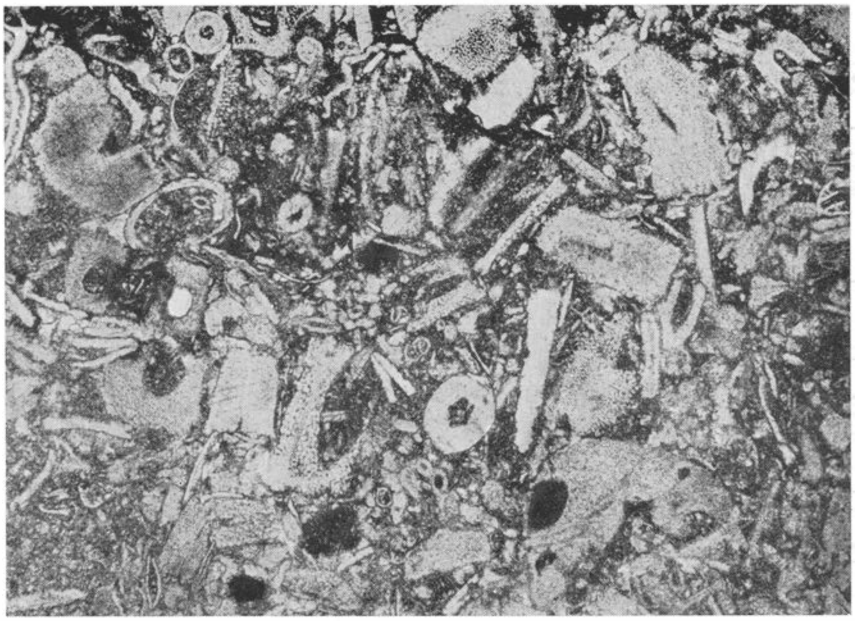

Fig. 96. Limbata limestone with pelmatozoans. Matrix: fine-grained fragments, microcrystalline calcite and hematite dust. Lower Ordovician. Resmo. Öland. (Prep. 6579, photo 1342.) — 20×.

Limbata limestone, Resmo.

Macro: Finely crystalline, glistening, grey with varying mixture of red and yellow. Isolated macrofossils, e. g. pygidium of *Megalaspis limbata*.

Micro: Fragment limestone with abundant crinoidal and other fragments less than 1 cm (fig. 96). Matrix of microcrystalline calcite (grains 5—15 μ) and micro-coquina with strongly corroded, recrystallized fragments (10—50 μ). The pigment (ferric oxide and hydroxide) is enriched in patches. Pyrite is absent, as are grains of glauconite. In isolated cases glauconite has been observed as an impregnation in crinoidal fragments.

Formation: Typical microcoquina deposited in slightly agitated, shallow water with oxidizing environment.

The sample belongs to the boundary layer of the Limbata zone with the Lower Asaphus limestone. According to MOBERG (manus.) this boundary layer is characterized in southern Öland by an abundance of crinoidal fragments.

Limbata limestone, Köpings klint (Cliff of Köping).

Macro: Typical dense, brownish-red limestone, uniform in colour but occasionally with distinct corrosion-surfaces, marked by a yellowish-grey band. The limestone contains scattered carapaces of trilobites and shells of brachiopods.

Micro: Microcrystalline matrix (grains 5—15 μ) with abundant microcoquina (25—50 μ) and some larger fragments, strongly corroded and recrystallized. The pigment, red hematite dust, is submicroscopic but enriched between the calcite grains. At the corrosion-surfaces the boundary between the lower part, which has little pigment, and the strongly pigmented upper part may be very distinct. Thin shells stick up over the corrosion-surface, indicating that only chemical corrosion and slight stirring up have taken place (fig. 17, p. 35). That the colour-pigmentation may be secondary in some parts of the sediment is shown by the fact that the mud enclosed in shells may be unpigmented, whilst the sediment around the shell is strongly coloured.

Formation: The limestone has been formed by deposition of extremely fine microcoquina (calcareous mud) with a varying percentage of argillaceous and ferric material. Consolidation occurred to a certain extent before stirring-up and chemical corrosion created a surface on which mud with coarse fragments and hematite pigment were deposited together.

Limbata limestone at Bruddestad boathouses.

Macro: Dense, greyish-violet (reddish-grey) limestone (dark-grey near bedding planes) in bed of 6 cm. The bedding planes are on the whole parallel but unevenly knobby and pitted, corroded. They have a thin coating of glauconite. Scattered macrofossils are visible in the bed, mostly carapaces of trilobites.

Micro: Microcrystalline (grains 5—15 μ), even-grained matrix, particularly rich in microcoquina (grains 10—50 μ) with strongly decayed small fragments (fig. 97). One or two small grains of glauconite. Colour-pigment (ferric oxide) extremely finely-divided between crystals and grains.

Formation: Typical calcareous-mud deposition in calm, shallow water. Oxidizing environment.

Limbata limestone at Sandvik harbour.

In northern Öland the lowermost Ordovician limestones are not everywhere accessible above sea-level. In certain places, e. g. at Horns udde, it is possible to study even Cambrian strata in the coastal sections but both north and south of this site Ceratopyge or Orthoceras limestone forms the base of the accessible section.[1] At Sandvik harbour, 25 km north of Borgholm, the Limbata limestone is exposed in a quarry. The sedimentary series is as follows (WIMAN 1904):

e. (uppermost) Crumbly, greatly weathered limestone
d. Grey limestone with faint tinge of red. Cleaves into four beds, "sheets" (of 0,25, 0,15, 0,20, and 0,22 m resp.) . . . . 0.76 m

[1] See BOHLIN 1949, p. 554 and 1955, p. 125.

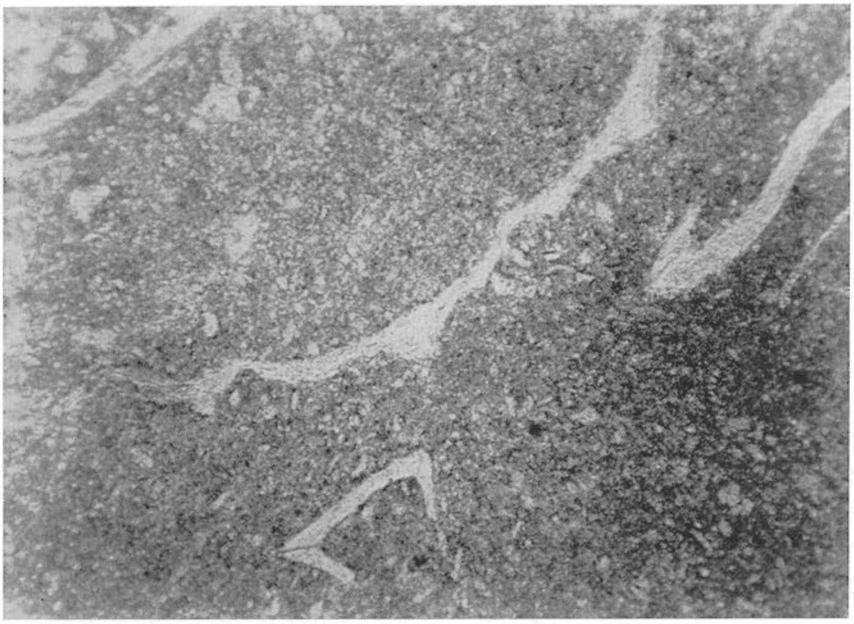

Fig. 97. Microcoquina limestone with strongly corroded fragments. Limbata limestone, Lower Ordovician. Bruddestad, Öland. (Prep. 6923, photo 1326.) — 60 ×.

c. Grey, faintly brown-banded limestone with strongly red-coloured bedding planes with hematite concretions. Weathered it is reddish-yellow, variegated. Cleaves into 3—4 beds. — "Blodlägspacken" ("The Bloody Layer") . . . . 0.47 m
b. Brownish-grey limestone, tinged with red and reddish-grey. Cleaves into a large number of beds (of 0,06—0,10 m) . . . . 1.90 m
a. Green (glauconitic) limestone (Planilimbata limestone)

The above-mentioned section conforms well with the development found in Limbata limestone elsewhere in northern Öland. According to Bohlin (1949, p. 547) the following standard section is found for northernmost Öland:

Zone with *Megalaspis limbata*	Greyish-red limestone, free from glauconite; dense. "Blodläget" ("The Bloody Layer"). Red limestone. "Blommiga blad" ("The Flowery Sheet")

Bohlin (1949, p. 532) points out that "The Bloody Layer" is a very characteristic bed and writes: "The bed contains within a thickness of about 12 cm three thin layers with 'warts' of hematite .... (best developed somewhat above the middle of the bed) .... These have a diameter of usually 2 or 3 cm and they lie scattered all over the bedding planes at fairly equal intervals (a few cm). At least in some cases the hematite must have accumulated around fossils. ... Cross-sections through the warts, ... show that they are sharply confined upwards whereas downwards they

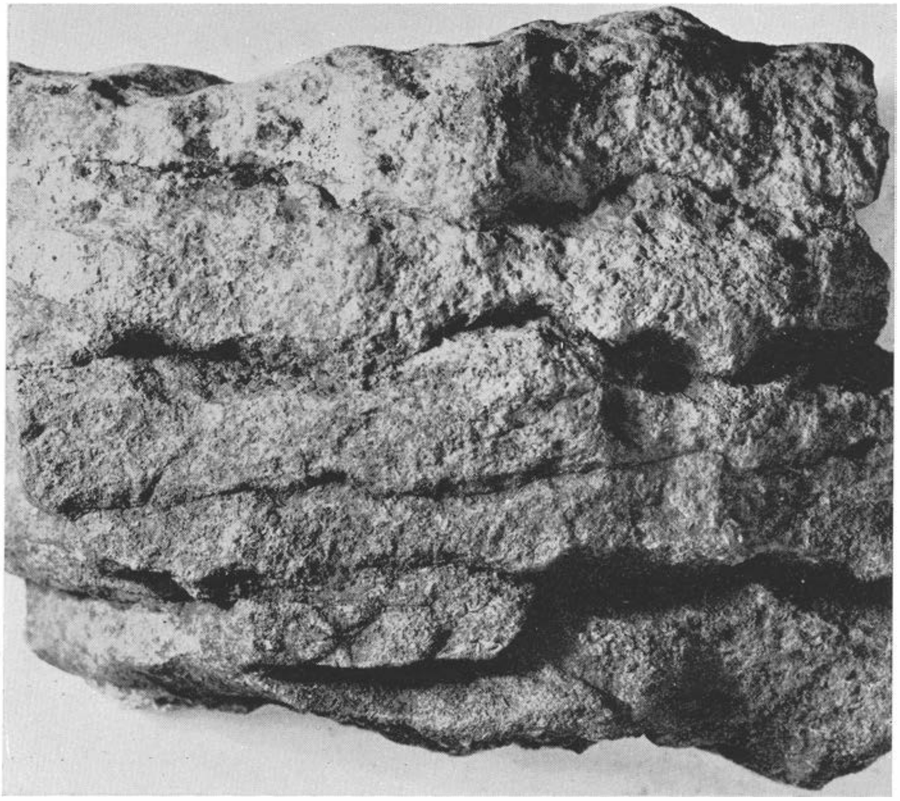

Fig. 98. Thin-bedded limestone. Asaphus limestone, Lower Ordovician. Resmo, Öland. (Photo 1495.) — $^1/_1$.

grade into normal limestone. (The hematite was precipitated on the surface and penetrated to a depth of a few millimetres between the small shell fragments which build up the limestone.) ... The bed undoubtedly represents a unique chemical or biological course of events effected by an occasional composition of the sea water, and occasional flora of bacteria (or organisms of some other kind), or the like."

Concerning the basal bed of the Limbata zone, "The Flowery Sheet",[1] Bohlin (ibid. p. 534 note) writes the following: "... an originally red bed in which the funnel-shaped pits were formed by corrosion. These pits are coated with glauconite on their walls and filled with material which forms the bed on top. The limestone has also been influenced chemically in other ways so that large portions have taken on a yellowish-brown (ochre) colour. The result is a variegated rock in which the colours (red, ochre, and green) are about equally represented, and each forms large patches on the surface."

[1] "The Flowery Sheet" is mentioned also as the uppermost bed of the Planilimbata limestone (Bohlin 1955, p. 117).

Asaphus limestone in Öland.

The Limbata limestone of Öland grades upwards into the Asaphus limestone. MOBERG (1890) distinguished two zones: Upper and Lower Asaphus limestone. In northern Öland, where the limestone has a partially different development, BOHLIN (1949) distinguished three zones with *Asaphus lepidurus*, *A. expansus*, and *A. raniceps* resp.

In *southern Öland* there is no lithologically marked boundary between the Lower Asaphus limestone and the beds below, the Limbata limestone. The light-red or greyish-red colour does not change at the zonal boundary. Not until a good bit further up in the Asaphus limestone does the limestone become grey or greyish-green. The rock is thin-bedded (1—4 cm) (fig. 98). The bedding planes are uneven but without deep corrosion-cavities. The uppermost two beds contain mass accumulations of cystoidean tests (*Sphaeronites pomum*). These index strata of southern Öland are not found in the northern part of the island.

In *northern Öland* the reddish-grey, glauconite-free Limbata limestone is overlain by grey, glauconitic Lepidurus limestone, which grades upwards into likewise grey and glauconitic Expansus limestone. A typical feature of the latter is the presence in the lower beds of an oolite-like texture with dark, elliptical grains. The upper beds of the Expansus zone are somewhat marly, like the Sphaeronites bed in southern Öland.

A few examples will be given of the character of the rock in the Asaphus zone.

Lower Asaphus limestone, Ottenby.

(Lower part)

Macro: Thin-bedded (2 cm), crystalline, medium-grained, glistening, light-red, mottled.

Micro: Fragment limestone with abundant crinoidal and other small fragments (0,1 mm), corroded and occasionally with crust of calcite crystals. Matrix, partly cryptocrystalline mud, partly larger calcite crystals, forms heterogeneous interstitial matter between the fragments (fig. 99). Pigmentation with hematite dust only in patches in the matrix. Some of the fossil fragments are strongly pigmented, others not at all. Concentric but irregularly shaped lumps of hematite dust occur sporadically.

Diagenesis: Strong recrystallization of the matrix calcite.

Formation: The limestone has been formed by accumulation of fragments of different character, e. g. crinoids with or without pigmentation, and from a mixing of materials with different sedimentary character, e. g. red, strongly hematite-impregnated portions in a grey matrix without hematite. The limestone has been formed from mud originating from different environments. It is a sub-littoral, shallow-water formation deposited in slightly agitated water.

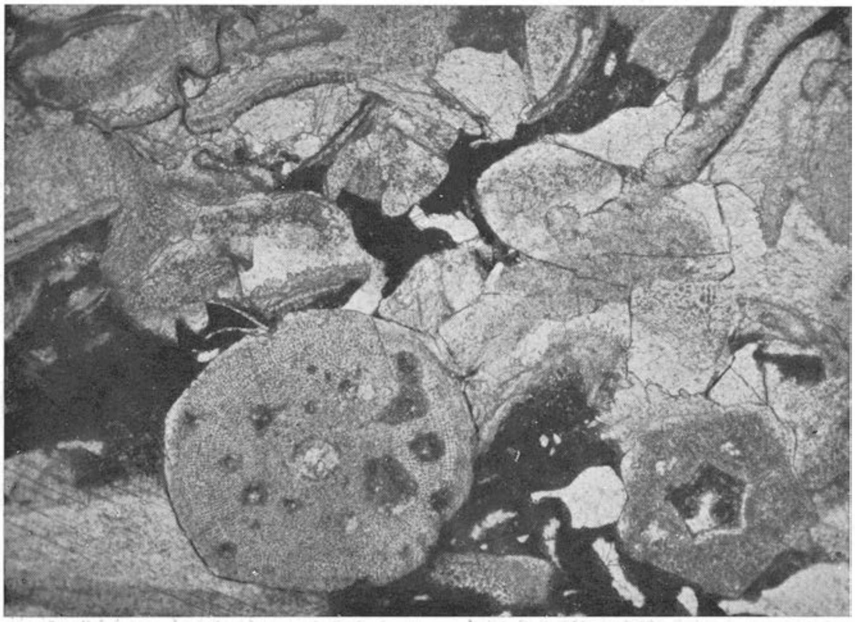

Fig. 99. Fragment limestone. Matrix partly coarse-crystalline calcite, partly argillaceous, cryptocrystalline hematite dust. Lower Asaphus limestone, Lower Ordovician. Ottenby, Öland. (Prep. 6628, photo 1639.) — 20×.

Lower Asaphus limestone, Köping.

Macro: Thin-bedded, grey, finely crystalline, compact without noticeable content of argillaceous matter.

Micro: Fragment limestone crowded with small fragments of crinoids and other fossils (fig. 100). The matrix consists of fine-grained calcite. Pigmentation appears slightly in the matrix, more clearly in individual fragments. Small grains of glauconite have been observed.

Diagenesis: Normal recrystallization of the matrix calcite.

Formation: Calcareous mud formed by accumulation of greatly crushed shell and crinoidal fragments. Deposition in shallow water in non-oxidizing, probably reducing environment with dissolution of the calcareous fragments.

Lower Asaphus limestone, Resmo.

Uppermost part = *the Sphaeronites bed.*

Macro: Two thin beds, together 5 cm of dense limestone, somewhat marly, dull, greenish-grey. Tests of cystoideans (*Sphaeronites pomum*) crowd the rock. They are either filled with dense, greenish-grey mud or with pure calcite crystals.

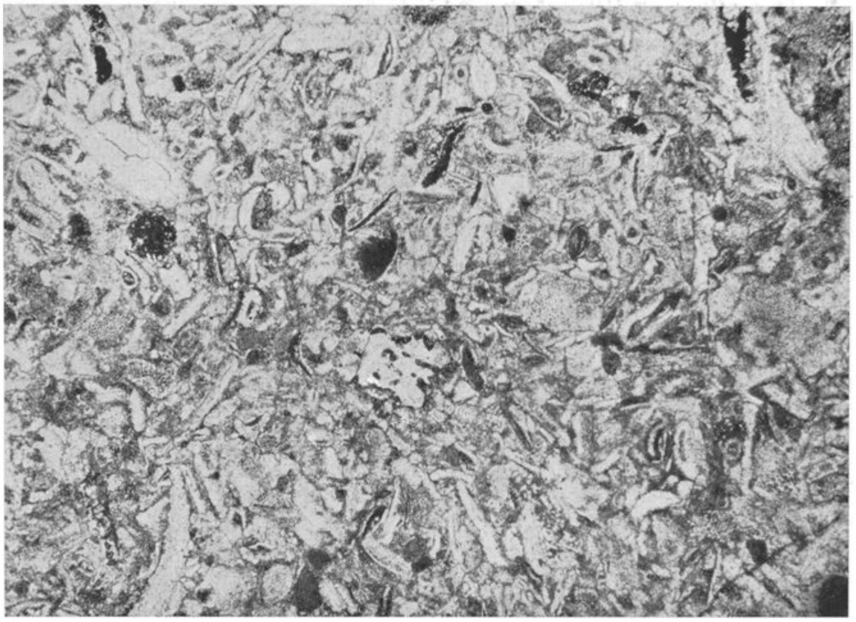

Fig. 100. Fragment limestone. Lower Asaphus limestone, Lower Ordovician. Köping, Öland. (Prep. 7559, photo 1344.) — 20×.

Micro: Fragment limestone crowded with bits of cystoideans, crinoids, and trilobites. The fragments are corroded but not pigmented. The matrix consists of microcrystalline calcite with pigment of argillaceous substance. The latter is found particularly abundantly in the cystoidean tests (fig. 101).

Diagenesis: Crystallization of the calcite of the matrix.

Formation: Calcareous mud deposited in shallow, somewhat agitated water. Probably reducing environment, definitely not oxidizing.

Lower Asaphus limestone, Hälludden.

(Expansus limestone)

Macro: Crystalline, compact, solid, with dark-green or black grains (glauconite). Whole carapaces of trilobites are fairly common.

Micro: Fragment limestone, typically granular with small, worn, rounded fragments. Glauconite grains (0,3 mm) with dense, dark-green peripheral part and light-green core (fig. 102). Glauconite also occurs as an impregnation in the porous parts of the encrinite fragments. Matrix of calcite crystals.

Diagenesis: Crystallization of the matrix.

Formation: Calcareous mud with allochthonous glauconite deposited in shallow water and weakly reducing environment.

Fig. 101. Fragment limestone with test of *Sphaeronites*. Asaphus limestone, Lower Ordovician. Resmo, Öland. (Prep. 7560, photo 1347.) — 20×.

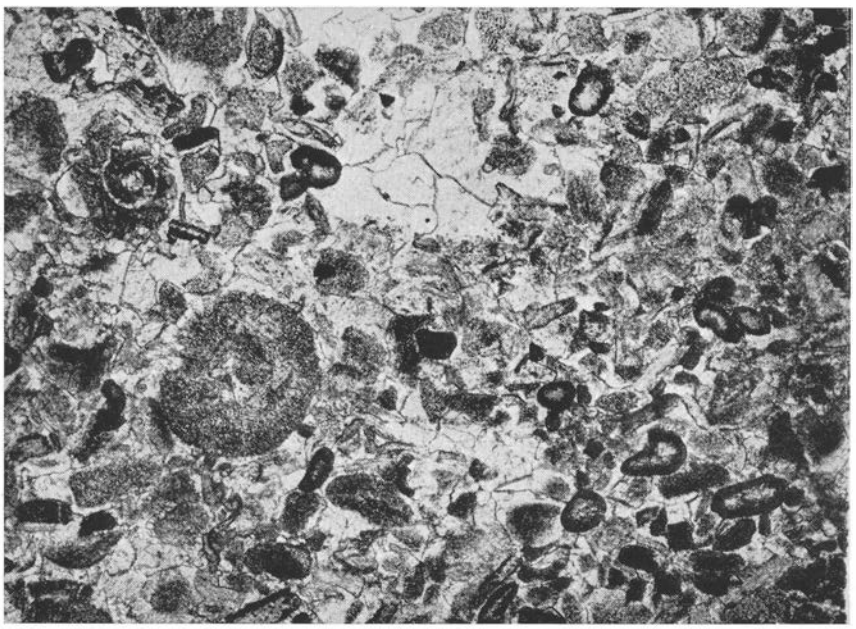

Fig. 102. Granular, glauconitic fragment limestone with crystalline matrix. Peripheral part of glauconite grains dark-pigmented. Lower Asaphus (Expansus) limestone, Lower Ordovician. Hälludden, Öland. (Prep. 6925, photo 1346.) — 20×.

Upper Asaphus limestone.

In *southern Öland* the Upper Asaphus zone consists mainly of strongly coloured, red and brownish-red limestone, at the bottom in thin, at the top in relatively thick beds. The basal strata are grey with tinges of red or green. The gradation from Lower to Upper Asaphus limestone occurs without marked lithological change in the sediments. The cystoids, typical of the uppermost beds of the Lower Asaphus limestone, are also characteristic of a few beds of the Upper Asaphus limestone, but they appear there in smaller forms.

In *northern Öland* there is a variation in the sediments like that seen in the southern part of the island. The grey, glauconitic limestones of the Lower Asaphus limestone (the Lepidurus and Expansus limestones) are overlain by a mainly grey, not very glauconitic Upper Asaphus limestone (Raniceps limestone). How the boundaries are to be drawn between the various zones, and which beds in northern Öland were deposited at the same time as e. g. the Sphaeronites bed of southern Öland, have been made clear by BOHLIN'S investigations (BOHLIN 1949 and 1955) and the description of the microlithology of the limestones by V. JAANUSSON (1955).

Upper Asaphus limestone, Möckleby.

Macro: Deeply reddish-brown, dense limestone with greyish-green, winding (worm) burrows. Some carapaces of trilobites.

Micro: Abundant fragments of trilobites, ostracods, brachiopods, crinoids, and cystoids (fig. 103). The matrix is microcrystalline. Pigment of hematite dust between the calcite crystals and as dense lumps. The pelmatozoan fragments are sometimes pure, sometimes pigmented.

Diagenesis: Crystallization of the matrix calcite.

Formation: Accumulation of small fossil fragments in slightly agitated water. Oxidizing environment.

Upper Asaphus limestone from Alvaret at Resmo.

Macro: Bed of 8 cm, on weathering divided up into four uneven, 1—3 cm thick layers. Crystalline, glistening, light red-mottled.

Micro: Fragment limestone. Numerous crinoidal fragments, partly hematite-pigmented. Strongly corroded cystoids. Trilobite fragments relatively smooth, often with hematite coating (fig. 104). Matrix: calcite aggregates with varying content of hematite-pigment.

Diagenesis: Crystallization of the matrix calcite.

Formation: Calcareous mud deposited in slightly agitated shallow water. Oxidizing environment.

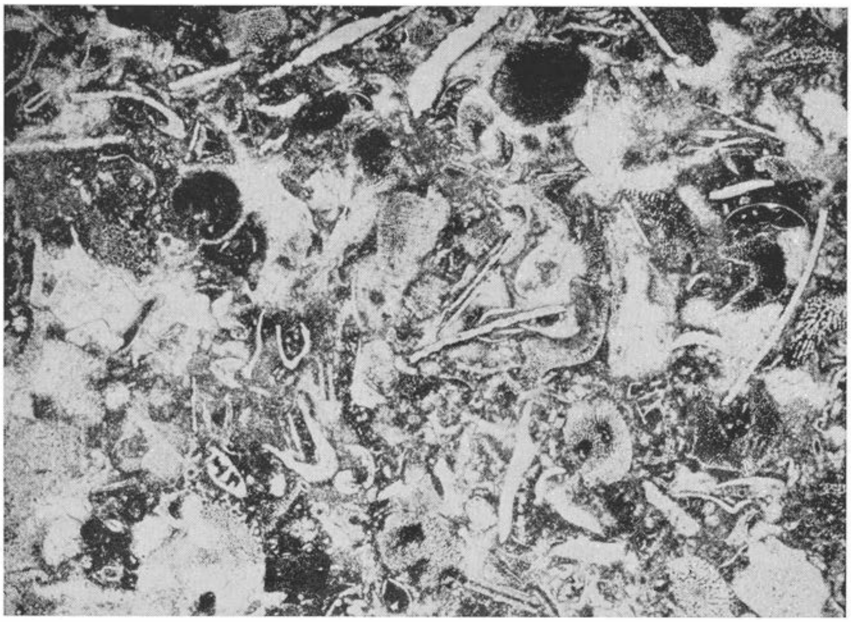

Fig. 103. Fragment limestone with pelmatozoans etc. Matrix microcrystalline, with hematite dust. Upper Asaphus limestone, Lower Ordovician. Möckleby, Öland. (Prep. 6618, photo 1343.) — 20×.

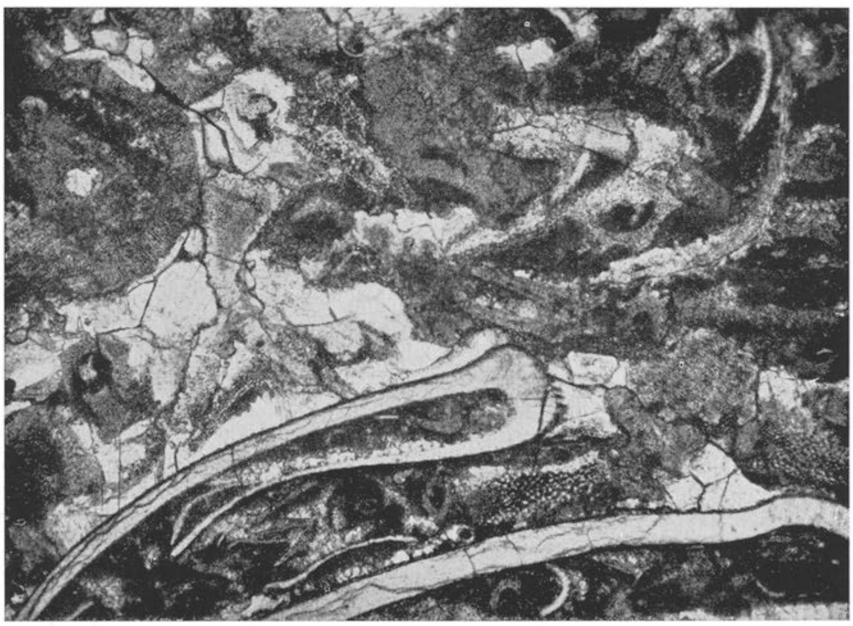

Fig. 104. Fragment limestone with trilobites and pelmatozoans. Matrix partly coarse-crystalline, partly microcrystalline with hematite dust. Upper Asaphus limestone. Alvaret, Resmo, Öland. (Prep. 3259, photo 1640.) — 20×.

Gigas and Platyurus limestone.

Overlying the Upper Asaphus limestone in southern Öland there is a series of limestones poor in fossils, which in turn are covered by Gigas and Platyurus limestone. All these limestones are finely crystalline, thin-bedded, and as a rule uniformly red. Apart from the index fossils, *Megalaspis gigas* and *Asaphus platyurus*, there are, especially in the upper strata, orthoceratites, locally cystoids (*Echinosphaerites*), too. The very uppermost strata are light-grey.

In northern Öland the Gigas and Platyurus limestone has a more varying appearance. Finely crystalline, bright-red forms are found but grey, greyish-green, and variegated, too (see BOHLIN 1949 and 1955).

Gigas limestone, Brunnby Canal, Öland.

Macro: Bed 7 cm, dense, brownish-red with green streaks (worm tracks?). Uneven bedding planes. The limestone glistens with cleavage-surfaces of pelmatozoan fragments.

Micro: Fragment limestone. The rock is for the most part rich in crinoidal fragments, 0,01—0,5 mm (fig. 105). The matrix consists of fine-grained, calcite aggregate, grains 0,005—0,015 mm, with submicroscopic pigment of hematite dust. The crinoids are also pigmented.

Formation: Calcareous mud deposited in tranquil, shallow water. Oxidizing environment.

Another bed from the Gigas limestone at Brunnby Canal, with numerous pygidia of *M. gigas*, has greyish-green, irregular portions in the brownish-red mass. Microscopically this bed is similar to the one described above.

Platyurus limestone, Brunnby, Öland.

Macro: Bed with uneven bedding planes, 3—5 cm thick. Finely crystalline — dense, somewhat glistening. The colour is uniformly brownish-red with no grey or greyish-green.

Micro: Fragment limestone. Small, smooth-shelled ostracods, 0,3—0,6 mm. Abundant crinoidal fragments, 0,2—2 mm, often strongly hematite-pigmented. Matrix crystalline, grains approx. 0,01 mm. Pigment of hematite dust (prep. 7561).

Formation: Calcareous mud deposited in tranquil, shallow water. Oxidizing environment.

Fig. 105. Gigas limestone. Lower Ordovician. Brunnby, Öland. (Prep. 3260, photo 1688.) — 20×.

The Orthoceras limestone of Västergötland.

In Västergötland, as in Öland, the Asaphus series consists largely of limestone, Orthoceras limestone. It also exhibits similar lithological variations in the two fields. The thickness of the series is usually about 40 m in Västergötland, but it reaches over 50 m on Kinnekulle.[1]

The Orthoceras limestone has long been quarried in Västergötland, and the general character of the rock in various parts of the series of strata has been relatively well known to those who have worked the limestone for various reasons. The individual beds in many cases have been given separate names, usually with reference to their technical value. The series of strata as a whole has also been popularly divided into four sections:

Leversten (Upper grey limestone)
Övre rödsten (Upper redstone)
Täljsten (Lower grey limestone)
Undre rödsten (Lower redstone)

---

[1] Of the works dealing with the Orthoceras limestone of Västergötland the following may be mentioned: Linnarsson 1869, Holm 1901, Munthe 1906, von Post 1906, Thorslund 1937, Westergård 1943, Tjernvik 1956.

The Orthoceras limestone of Västergötland has only recently and to a small extent been systematically investigated and described from a stratigraphical and paleontological point of view (TJERNVIK 1956). We do, however, know the series of strata well enough to distinguish in it the same zones as in Öland. Some selected types of the rock in the various zones will be illustrated below.

Planilimbata limestone in Västergötland.

The Lower Ordovician has a greatly varying development in Västergötland. The Planilimbata limestone, like the Ceratopyge limestone, can be well developed, replaced by shales, or entirely absent. As an example of a series of strata, mention may be made of the section at Änge, where the following strata were measured (THORSLUND 1937, 147):

Limestone with *Megalaspis limbata*	—
Grey shales with *Phyllograptus densus*	2,8 m
Grey limestone with *Megalaspis planilimbata*	0,4 m
Glauconitic limestone	0,2 m
Dense, grey limestone. Ceratopyge limestone	0,3 m
Glauconitic shale	1,1 m

In fig. 106 is shown the appearance of the Planilimbata limestone (according to TJERNVIK 1956) in three other places in Västergötland: Mossebo on Hunneberg, a quarry south-east of Ålleberg, and Stora Stolan on Billingen. In places where the Planilimbata limestone is partly or wholly replaced by shale, as at Nygård on Hunneberg, thin limestone beds can be found in the shale. Such is the case in the upper part of the shale series, which in places, for example at Hällekis (cf. TJERNVIK 1956, 142), may be younger than the Planilimbata limestone. Examples of the lithological character of these limestone beds will be illustrated in connection with Planilimbata limestone of normal development.

Planilimbata limestone at Käpplunda, Billingen.

On Billingen the Cambrian alum shale is overlain by a thin bed of Ceratopyge limestone and glauconite shale, which in turn is covered by Phyllograptus shale. Above the shale follows Planilimbata limestone. It has a typical development in the quarry at Käpplunda, north of Skövde. The different beds vary in thickness (6—10 cm), but are otherwise quite similar. One of them, situated approx. 1 m above the alum shale, will be illustrated.

Macro: Dense, brittle, light-grey bed with darker brownish-grey portions. Bedding planes uneven with irregular grooves and ridges. Pyrite in small cubes.

Micro: Finely crystalline, granular (grains approx. 0,01 mm), with grey-black pigment in varying quantity. The darker portions are rich in small pyrite crystals,

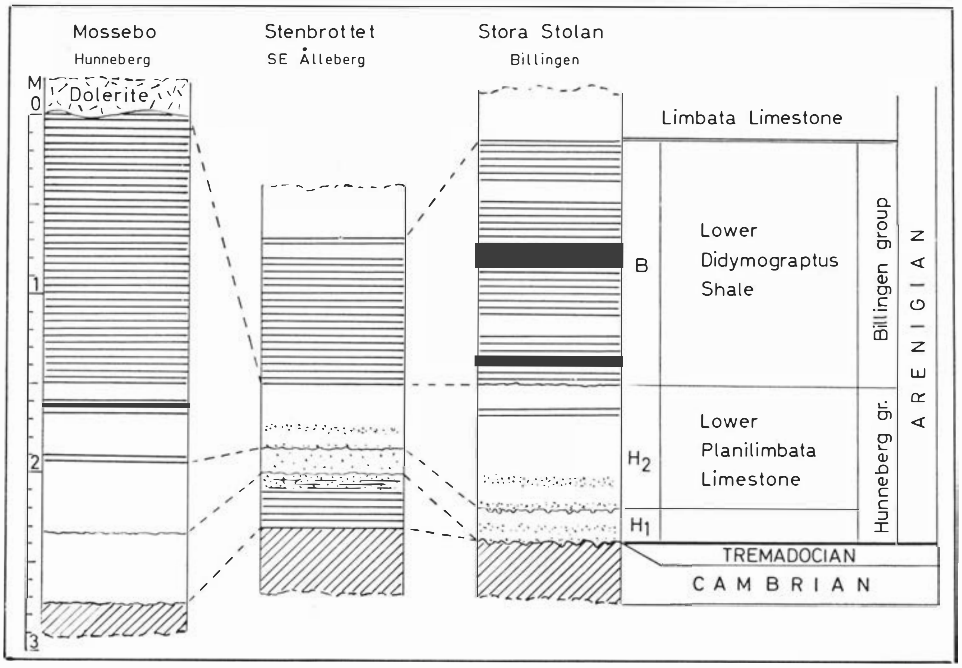

Fig. 106. Sections through the Planilimbata limestone of Västergötland (acc. to TJERNVIK 1955).

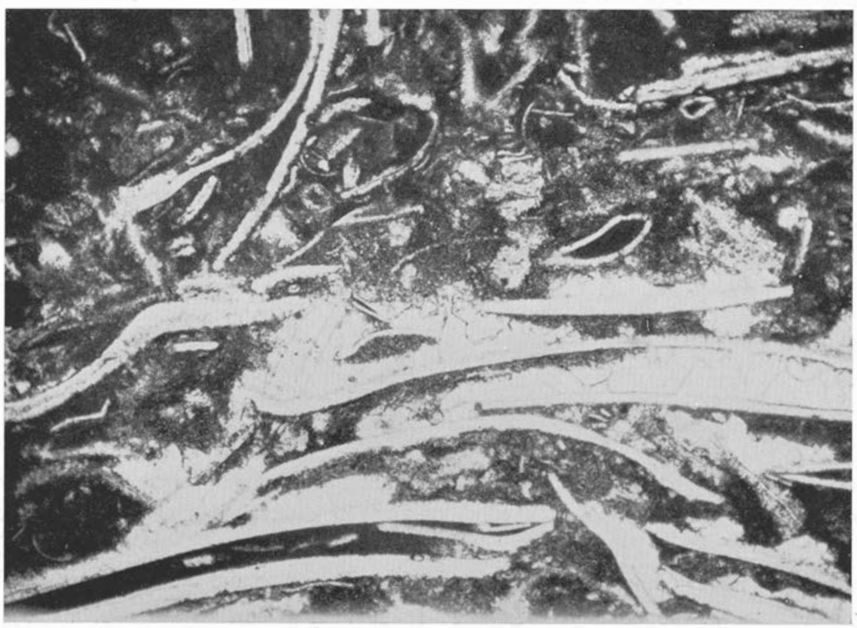

Fig. 107. Planilimbata limestone with fragments of trilobites. Matrix argillaceous, microcrystalline calcite. Lower Ordovician. Käpplunda, Västergötland. (Prep. 7292, photo 1607.) — 20×.

and the border between the light and the dark parts is sharply defined. Fragments of trilobites are present in abundance, and also whole carapaces (fig. 107). Pelmatozoan fragments only sparingly.

Formation: Calcareous mud rich in fossil fragments deposited in shallow water. Organic matter has been present in such abundance that a reducing environment has been created.

Planilimbata limestone, Ulunda, Billingen.

Between Ulunda on the west side of Billingen and Käpplunda on the east side there is a distance of 20 km. There are certain differences between the series of strata in the two places and in the lithological character of the rocks. A typical limestone from the Planilimbata zone at Ulunda will therefore be illustrated.

Macro: Dense, almost like lithographic limestone, greyish-white but faintly brown near the bedding planes. Bed of 5 cm divided into 4 thinner, out-thinning, uneven layers. Bedding planes rough.

Micro: Microcrystalline — cryptocrystalline grains generally less than 0,001 mm. (Worm-) Burrows with coarse calcite grains (0,01—0,03 mm) traverse the dense mass. Fine micrococoquina are fairly abundant; ostracods and pelmatozoans are only sparingly found. Pyrite in small, scattered crystals. Glauconite has not been observed. (Prep. 7234).

Formation: Calcareous mud deposited in calm water.

Planilimbata limestone(?), *Hällekis, Kinnekulle.*

The soft, green argillaceous shale which underlies the Limbata limestone contains beds of dense, green, somewhat marly limestone. In the latter glauconite appears, partly in the form of allothigenic grains, partly as authigenic flocks between the calcite grains. Under the microscope the rock appears finely crystalline, even-grained (grains 0,01—0,02 mm). The glauconite grains are partly small and diffuse, 0,02—0,05 mm, partly larger, rounded, 0,2 mm. There are practically no fossil fragments (prep. 7284).

The uppermost limestone bed, of 2—3 cm, like the underlying shale, is full of worm-burrows. On the bedding plane they are preserved in full relief (fig. 108), but they appear only as thin, brownish-red tracks in the green marly shale.

Macro: Variegated, red-brown-yellow-green limestone, with irregular mixing of the colours, which grade into one another. Barytes in irregular, colourless, glass-clear crystals.

Micro: The major part finely crystalline, granular (calcite grains approx. 0,02 mm). Hematite dust and argillacous matter abundant as pigment. Microcoquina indistinct, corroded, and recrystallized. Glauconite in small isolated grains (0,05—0,1 mm). The barytes crystals are situated in the lower part of the bed partly surrounded by green, marly matter (fig. 109).

Fig. 108. Argillaceous limestone with "worm-burrows" on the bedding surface. Planilimbata limestone (?), Lower Ordovician. Hällekis, Västergötland. (Photo 1500.) — $^1/_1$.

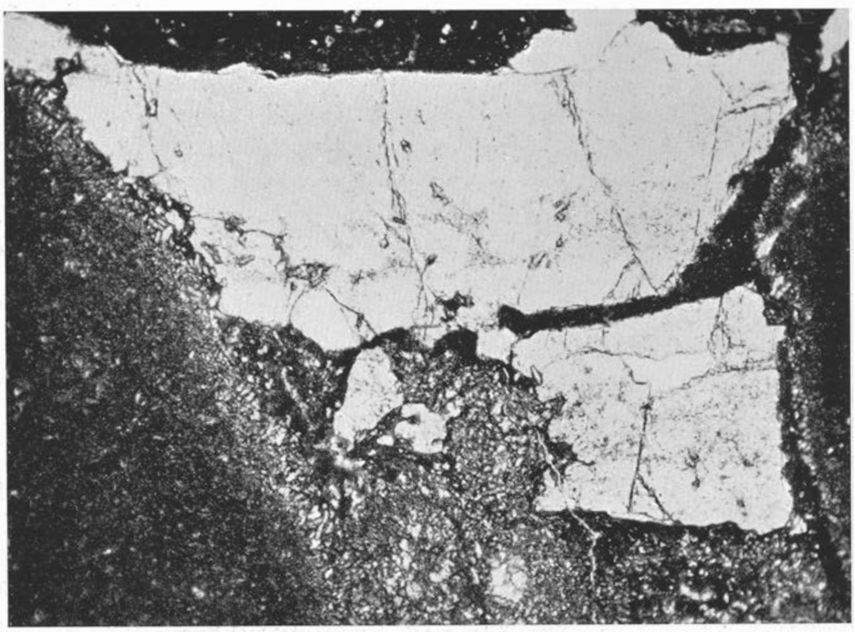

Fig. 109. Barytes crystals. Planilimbata limestone(?), Lower Ordovician. Hällekis, Västergötland. (Prep. 8767, photo 1591.) — 20×.

Formation: During decreasing sedimentation of argillaceous matter calcareous mud has been deposited in calm, shallow water. The red colour indicates an oxidizing environment, but the occurrence of green mud and a profusion of organic life (worm-tracks) show that, periodically at any rate, organic matter has been present in sufficient quantity for a reducing. The remarkable colour-mixing can partly be ascribed to the worms' working-over of the mud.

The Limbata limestone of Västergötland.

The diversity, above all in colour, found between the Planilimbata limestone of Kinnekulle and that of Billingen, is found in the Limbata limestone, too. The deep-red Limbata beds of Kinnekulle — Lower Redstone — correspond to light-grey limestones on Billingen.

The thickness of the Limbata limestone varies from one place to another. On Kinnekulle it has been measured as 20 m; on Billingen it is appreciably less. A characteristic of the Limbata limestone is even bedding with almost rhythmic alternation between limestone beds and thin marly layers. The individual beds and layers are of varying thickness.

Limbata limestone, Hällekis.

The Limbata limestone is excellently exposed at Hällekis in the cement factory's quarry, the Redstone quarry. The limestone beds are too thin and the marl-content too high for the stone to be suitable for building-stone etc.; it is all the better adapted for the industry which now exploits the deposit.

The lowermost part of the Limbata limestone, which at Hällekis is situated in and above the earlier-mentioned shale, consists of several beds of 5—10 cm. They are macroscopically dense, dull, variegated in green, red, and yellow. In certain beds the colours are mixed; in others, where one or more corrosion-surfaces have developed, there is a clearly marked border between the yellow band of the corrosion-surface and the overlying green and red calcareous mudstone. Barytes crystals have been observed in these beds, too, always in corrosion-cavities together with glauconite. (Rock specimen 5941.) Grains of glauconite may be enclosed in the barytes.

The Limbata limestone at Hällekis has a relatively uniform red colour in its upper part. The purer, more solid beds are of the same nature as the rock from Mörkeklev described below. The less solid beds consist of lumps of limestone in loose marl. They are of the same red colour as the solid beds.

Inside mud-filled shells of orthoceratites barytes has been found in crystals of about the same size, but not the same form as these described above from the Planilimbata limestone. The crystals are skeleton-like or unevenly corroded by dissolution. They have not been observed in the surrounding rock.

The special nature of the limestone will be illustrated with a sample that was taken from a hard bed (5 cm thick) in the Redstone quarry about 1,5 m from the bottom.

Macro: Dense, hard, somewhat flamy, yellow and red limestone, with both colours irregularly distributed but about equally well represented. The border is often sharply defined between a yellow portion and an overlying brownish-red one, but hazy between brownish-red and overlying yellow. Small depressions (corrosion-grooves) which occur in the yellow bands are filled with red matter. Glauconite coating has not been observed between different-coloured portions. The bedding planes are uneven but without deep corrosion-pits.

Micro: Microcrystalline (grains 3—10 μ) with varying, deep and faint, yellow and red pigmentation. Fragments larger than 1 mm, mainly of trilobites, occur in profusion. Pelmatozoans, gastropods, and ostracods have not been found. The matrix contains fine microcoquina. Glauconite occurs in occasional grains (50—150 μ) (prep. 7286).

Diagenesis: Slight recrystallization, but certain fragments have a crust of radiated calcite.

Formation: Deposition of calcareous mud in calm-water environment, partly strongly oxidizing.

Limbata limestone at Mörkeklev, Råbäck, Kinnekulle.

Macro: Dense, dull, uniformly brownish-red limestone with no yellow or green. The bed has no corrosion-surface but has an uneven bedding plane. Occasional macrofossils, grey, with waxy lustre (like chalcedony).

Micro: The major part microcrystalline (calcite grains approx. 5 μ), even-grained. Abundant submicroscopic hematite dust between the grains. Microcoquina (less than 0,2 mm) and fragments (0,2—2 mm) are abundant, larger trilobite fragments rare. Pelmatozoans have not been observed. Pyrite and glauconite are absent (prep. 6685).

Formation: Calcareous mud with greatly oxidized matter deposited in calm water.

Limbata limestone, Käpplunda, Billingen.

Macro: Dense, light-grey, with faintly reddish-grey, compact middle portion and looser greenish-grey, marly portions nearest bedding planes. Inside the bed a corrosion-surface marked by a dark-brown streak of pigment. Bed 8 cm, disintegrating into thin slabs along marly interlaminations.

Micro: Major part microcrystalline (calcite grains 5—10 μ), irregularly pigmented with argillaceous matter. Abundant microcoquina (0,03—0,3 mm), coarser fragments (0,3—3 mm) less abundant. Large fragments of trilobites and pelmatozoans occur sparingly. No pyrite or glauconite is found. (Prep. 7294.)

Diagenesis: Complete recrystallization but without formation of coarse-grained calcite.

Formation: Calcareous mud and inorganic fine detritus deposited in calm water and at greater depth than on Kinnekulle. Neutral environment.

Limbata limestone, Ulunda, Billingen.

Macro: Dense, dull, light red-brown-grey.

Micro: Microcrystalline (calcite grains approx. 5 μ), even-grained. Pigment not very noticeable. Thin, corroded, recrystallized fragments of trilobites, ostracods, and encrinites occur in profusion. Occasional small gastropods. Crinoidal fragments not uncommon. Pyrite and glauconite are absent (prep. 7235).

Diagenesis: Matrix and fragments completely recrystallized.

Formation: Calcareous mud deposited in calm water and weakly oxidizing environment.

Asaphus limestone in Västergötland.

"Täljsten".

Between the "Lower Redstone" of Västergötland, the Limbata limestone, and the "Upper Redstone", the Gigas-Platyurus limestone, there are some grey limestone beds, which on Kinnekulle are called "täljsten" (=free-cutting stone). This part of the series of strata corresponds to the Upper and Lower Asaphus limestone of Öland. The thickness is only 1—2 m. The series contains some pure, solid beds, which are quarried and worked. As in Öland, the series contains beds full of cystoids (*Sphaeronites*).

Asaphus limestone, "Täljsten", Råbäck, Kinnekulle.

One of the least argillaceous, more solid beds of the Asaphus limestone, the "täljsten", has been extensively used for gravestones and has therefore been designated "likhall" (corpse stone) by the workers in the quarry. It has a thickness of 11—12 cm.

Macro: Fine-grained, glistening, with abundant small fragments of fossils. Larger carapaces of trilobites are rare. Glauconite is visible with a magnifying-glass as green grains and small, diffuse patches.

Micro: Major part recrystallized micrococquina with grains 3—10 μ. Large fossil fragments (0,1—2,0 mm) very abundant, but corroded and recrystallized (fig. 110). Most common are fragments of pelmatozoans, trilobites, and ostracods; less common small gastropods. Glauconite occurs sparingly, mostly as infilling and impregnation in fragments. Pyrite, too, has been observed as a rare impregnation.

Diagenesis: Complete recrystallization of calcareous mud and fragments without formation of large calcite crystals.

Fig. 110. Microcoquina limestone with corroded and recrystallized fragments of trilobites and pelmatozoans. Asaphus limestone ("Likhall"), Lower Ordovician. Kinnekulle, Västergötland. (Prep. 6933, photo 1592.) — 20 ×.

Formation: Deposition of calcareous mud in gently moving water without supply or retention of argillaceous matter in appreciable quantity. Authigenic glauconite as infilling and impregnation in the fragments indicates formation in a weakly reducing environment. Traces of an occasional change-over to an oxidizing environment are not found.

Asaphus limestone, Österplana, Kinnekulle.

Macro: Dense, dull, grey with faint tinge of green and with thin, dark bands marking uneven bedding planes in the 10 cm-thick bed. Irregularly tabular, glass-clear crystals of barytes are scattered throughout the bed.

Micro: Microcoquina limestone with glauconite grains (abundant). Major part finely crystalline, granular (calcite grains 0,01—0,03 mm). A confusion of small fragments, mostly of trilobites but also of pelmatozoans (fig. 111). Small gastropods occur sparingly. Pigment is found enriched in certain limited portions. The glauconite grains are mostly rounded and sometimes cracked, 0,1—0,4 mm. Glauconite also occurs as infilling in a few shells and as impregnation in pelmatozoans. The barytes crystals are irregular, skeleton-like.

Diagenesis: Slight crystallization of the calcareous mud. Formation of barytes crystals.

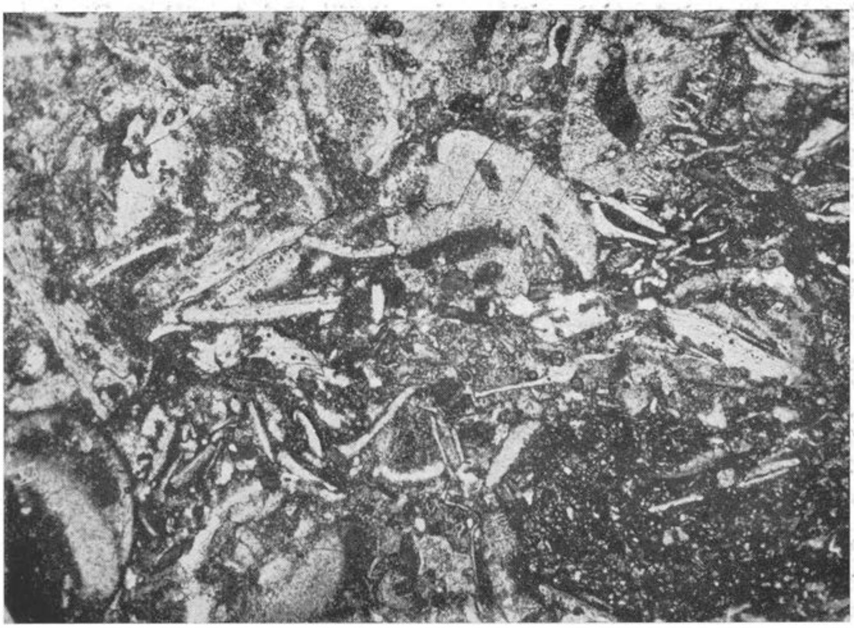

Fig. 111. Asaphus limestone ("Täljsten"), Lower Ordovician. Österplana, Västergötland. (Prep. 7298, photo 1606.) — 20×.

Formation: The limestone was formed by deposition in calm water of fine calcareous mud in which were mingled allothigenic grains of glauconite and fossil fragments. Non-oxidizing environment.

The Sphaeronites beds of the Asaphus limestone of Kinnekulle are thin and somewhat marly, like those of Öland. The purer and more solid (middle) portions have largely the same composition as the limestone described above, but they have a greater profusion of cystoids. The cystoidean tests may be closely packed together in places, elsewhere somewhat more sparse. They have often been halved through their upper part's being destroyed, whilst the lower part has been preserved embedded in the calcareous mud (fig. 112). How this destruction occurred is not known to the author, but it must have taken place before the bed was finally buried under deposited mud. The condition is particularly common in the bed containing the smaller type of *Sphaeronites* (balls 1—2 cm); less noticeable in the bed with the larger tests of 3—4 cm.

Asaphus limestone (*Expansus limestone*), *Käpplunda.*

Macro: Finely crystalline, glistening, dark-grey, tinged reddish-grey. Bedding planes uneven, with irregular grooves and ridges. Bed 10 cm.

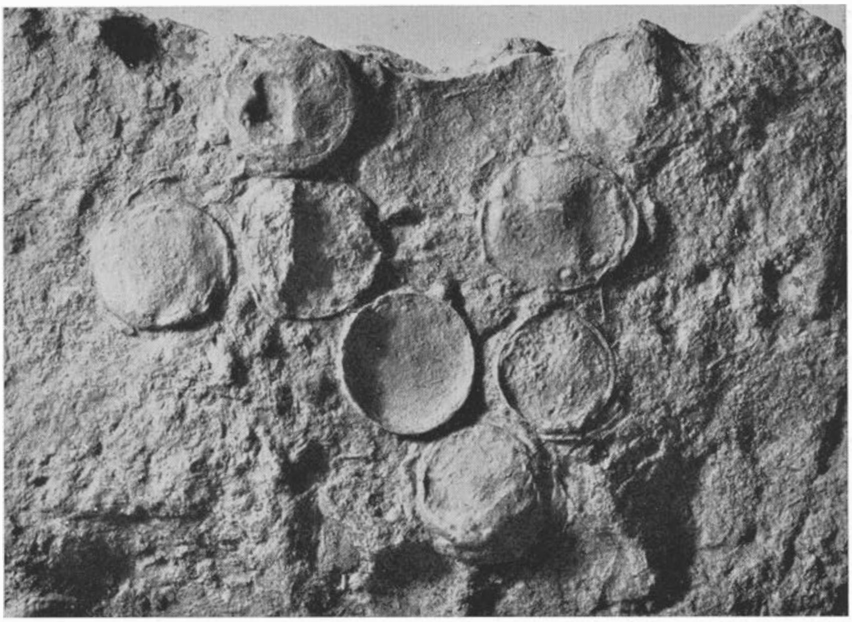

Fig. 112. Sphaeronites limestone with partly destroyed tests. Lower Ordovician. Österplana, Västergötland. (Photo 1503.) — $^1/_1$.

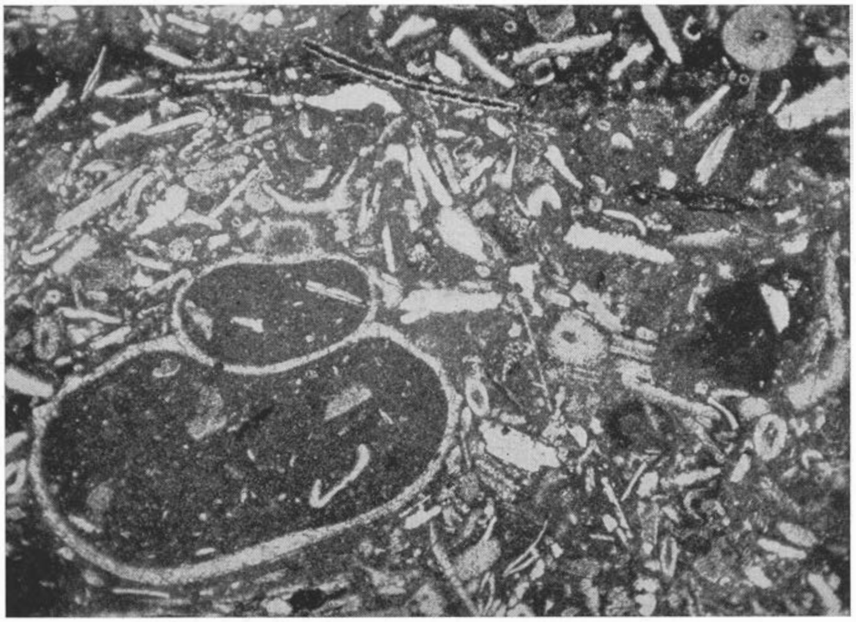

Fig. 113. Microcoquina limestone with argillaceous, microcrystalline calcite matrix. Asaphus (Expansus) limestone, Lower Ordovician. Käpplunda, Västergötland. (Prep. 7295, photo 1594.) — 20 ×.

Micro: Microcoquina limestone. Ground-mass finely crystalline, granular, with argillaceous pigment. Abundant small fossil fragments, corroded, diffuse, mostly 0,04—0,3 mm. Small shells of gastropods (approx. 3 mm), fragments of pelmatozoans, ostracods, and trilobites (fig. 113). Limonite in thin laminae and in some fossils. No glauconite or pyrite.

Formation: Calcareous mud with abundant microcoquina deposited in calm water.

Asaphus limestone, Öglunda.

Macro: Dense, dark-grey with irregular tinge of reddish-brown.

Micro: Microcoquina limestone. Major part microcrystalline, granular (calcite grains approx. 5 μ), with diffusely distributed pigment of argillaceous matter and limonite. Small gastropods, ostracods, fragments of trilobites, and pelmatozoans. No glauconite or pyrite.

Formation: Calcareous mud deposited in calm water and weakly oxidizing environment.

Gigas and Platyurus limestone in Västergötland.

"Upper Redstone" — "Upper red Orthoceras limestone"

As in Öland we find in Västergötland the Gigas and Platyurus limestone developed as a series of dense, dark brownish-red beds, indistinctly delimited from the underlying Asaphus limestone. The thickness of the series is about 11 m on Kinnekulle (Holm 1901); on Billingen it is more varied. Cephalopods are the most common fossils.

Gigas limestone, Råbäck, Kinnekulle.

The bed investigated belongs to the lower part of the Gigas limestone.

Macro: Dense, dull, deep brownish-red with irregular yellowish-grey portions. Yellowish-grey crust round orthoceratites. Barytes crystals, tabular, 10×3 mm, in yellowish-grey portions.

Micro: Microcoquina limestone, microcrystalline, granular (calcite grains 5—10 μ), abundantly pigmented with hematite dust. Fragments (0,2—2,0 mm) of pelmatozoans etc., fairly common. Small gastropods sparingly, ostracods more abundantly.

The yellowish-grey portions have the same texture and fossil content as the red, but they lack the latter's strong pigmentation. The boundary is sharp in parts, hazy in others, sometimes double, a condition which indicates infiltration. Accumulation of organic, reducing matter in certain patches may offer a natural explanation for the fact that these patches were not pigmented by oxidation and flocculation of limonite or hematite. No glauconite or pyrite.

Diagenesis: Complete but faint recrystallization of the primary mud.

Formation: Calcareous mud with abundant microcoquina and larger fragments deposited in calm water. Largely oxidizing environment.

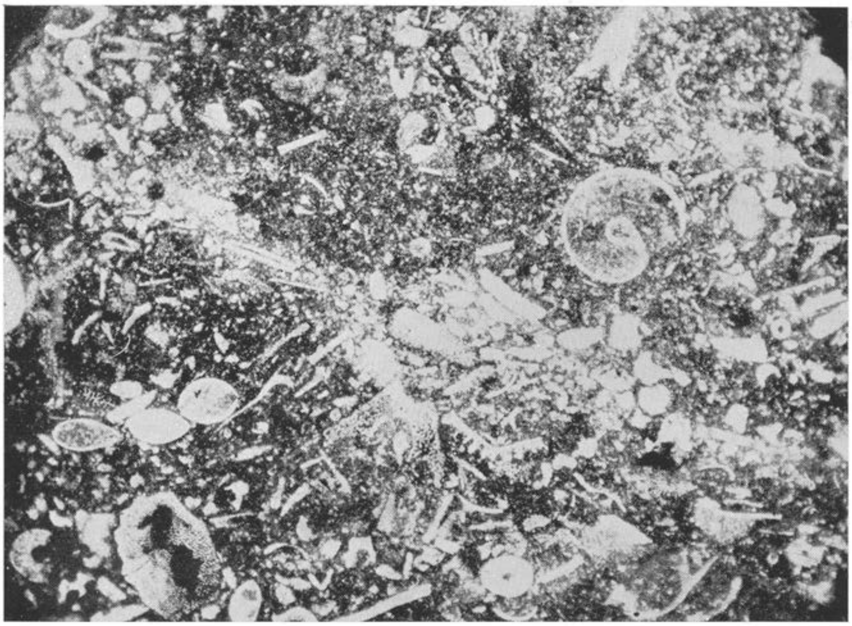

Fig. 114. Microcoquina limestone with small gastropods, ostracods and fragments of trilobites and pelmatozoans. Matrix microcrystalline, strongly pigmented with hematite. Gigas limestone, Lower Ordovician. Käpplunda, Västergötland. (Prep. 7296, photo 1610.) — 20 ×.

Gigas limestone, Käpplunda, Billingen.

The bed investigated lies uppermost in the quarry at Käpplunda. It belongs to the upper part of the Gigas limestone.

Macro: Dense but somewhat glistening, deep brownish-red limestone. Bed 6 cm, disintegrating into thinner layers of 1—3 cm. Bedding planes uneven.

Micro: Microcoquina limestone (fig. 114). Major part finely crystalline, granular (calcite grains 5—10 μ), abundantly pigmented with hematite, which is also found enriched in thin portions and in pelmatozoan fragments. Abundant small pelmatozoans and trilobite fragments; ostracods and gastropods less commonly. Glauconite and pyrite have not been observed.

Diagenesis: Faint recrystallization of the mud.

Formation: Calcareous mud deposited in calm water. Oxidizing environment.

The Orthoceras limestone of Östergötland.

Despite the fact that the Cambro-Silurian regions of Östergötland and Västergötland more or less border on one another, the rocks in the two regions have a somewhat different development. A number of rocks typical of the Orthoceras limestone of Östergötland will therefore be included in this survey. The series of strata has, however, only been subjected to a systematic stratigraphical investigation as far as the oldest zones are concerned (TJERNVIK 1956), and it is therefore impossible for the time being to carry out a comparison with corresponding strata in other counties. MOBERG (1890) proposed the following division:

<table>
<tr><th colspan="2">Öland</th><th>Östergötland
(according to LINNARSSON and TULLBERG 1882)</th></tr>
<tr><td rowspan="3">Asaphus limestone</td><td>Upper (pink)</td><td rowspan="4">Expansus limestone (at top red, lower down green)
Grey limestone ("likhall")
Heros limestone (grey)
Almost pure grey limestone
Pink limestone</td></tr>
<tr><td>Sphaeronite bed</td></tr>
<tr><td>Lower (grey)</td></tr>
<tr><td colspan="2">Limbata limestone</td></tr>
<tr><td colspan="2">Planilimbata limestone</td><td>Planilimbata limestone</td></tr>
</table>

At present it is not known how the Gigas and Platyurus zones of the Asaphus stage are developed in Östergötland.

The Planilimbata limestone of Östergötland.

The upper Cambrian series of Östergötland, consisting of alum shales and anthraconites, is covered by the alum shale of the Ceratopyge series, Dictyonema shale (with beds of calcareous sandstone), and glauconitic limestone with glauconite sand. These glauconitic strata have a thickness of less than 1 m (at Knivinge 0,3 m). There are, however, glauconitic beds in the overlying Planilimbata limestone, too. The series of strata has been investigated by TJERNVIK (1956), and the attached sections, fig. 115, are based on his work. Three selected rock types, from Knivinge, Västanå, and Borghamn, will be illustrated.

Planilimbata limestone, Knivinge.

Macro: Dense, light greyish-green, with deeply green-pigmented corrosion-surfaces. Abundant glauconite grains in the lower part of the bed. Pyrite: small crystals and aggregates.

Micro: Microcrystalline, even-grained (calcite grains approx. 5 μ). The lower part of the bed has abundant glauconite grains (0,5—2,5 mm) and trilobite fragments (2—5 mm) (fig. 116).

Formation: Calcareous mud slightly argillaceous deposited in at times calm, at times agitated water. The latter resulted in accumulation of glauconite grains and

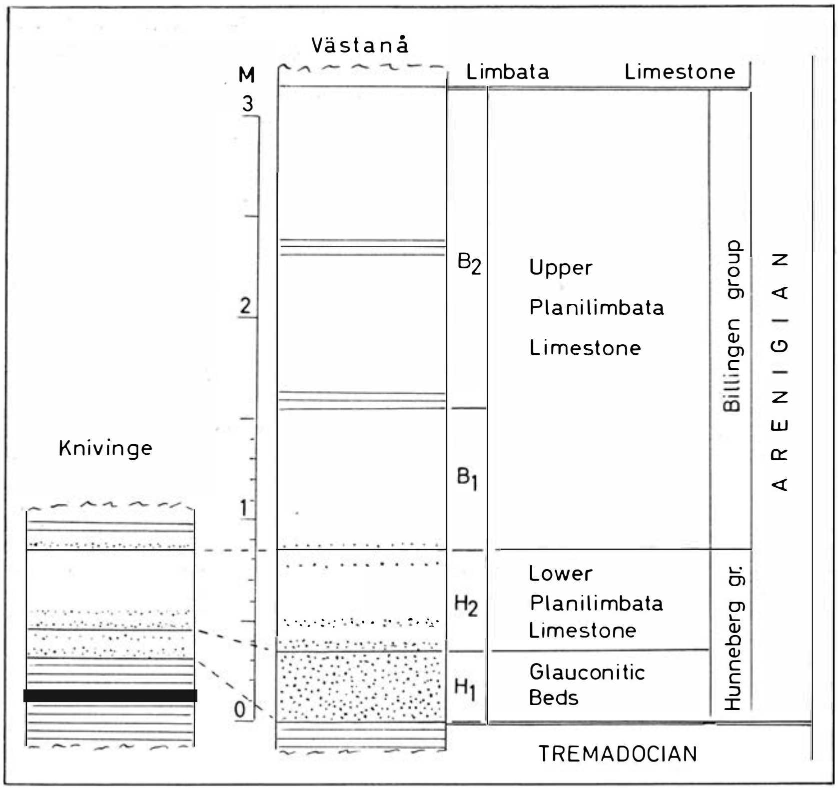

Fig. 115. Section through the Planilimbata limestone of Östergötland (acc. to TJERNVIK 1955).

fossil fragments, washing-away of mud, corrosion, and in connection with this deposition of glauconite on the corrosion-surfaces. Fairly rich precipitation of iron sulphide. Alternating neutral and reducing environment.

Planilimbata limestone, Västanå.

Macro: Dense, light greyish-green, with knobby bedding plane brown-coloured when weathered. A few cylindrical worm-trails. Abundant pyrite crystals. Pygidia of *Megalaspis planilimbata*. Bed 2—4 cm.

Micro: Finely crystalline, even-grained (calcite grains 5—10 μ); abundant micro-coquina, larger fragments only occasionally. Fossils recrystallized and often with a crust of radiated calcite. Glauconite partly as impregnation (on the corrosion-surface), partly as coating on and impregnation in larger fossils. Pyrite in small cubes.

Formation: Calcareous mud deposited in calm water. At times negative sedimentation with formation of corrosion-surfaces. Reducing environment.

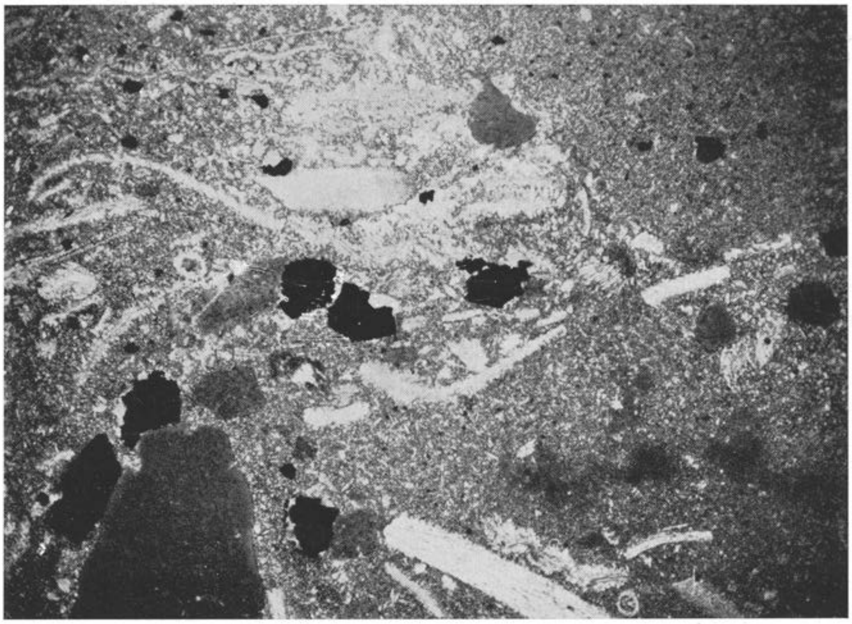

Fig. 116. Planilimbata limestone with recrystallized fragments, grains of glauconite (dark grey), and pyrite (black). Matrix even-grained, microcrystalline calcite and fragments. Lower Ordovician. Knivinge, Östergötland. (Prep. 7777, photo 1624.) — 20×.

Planilimbata limestone, Borghamn.

Of the three places in Östergötland from which Planilimbata limestone is mentioned here, Knivinge lies farthest to the east, Borghamn farthest to the west, and Västanå in the middle part and farthest to the north. The distance Knivinge-Borghamn is 47 km. As is apparent from the report, the limestone is remarkably similar in the three places.

Macro: Dense, light greyish-green, with uneven, marly bedding planes. Bed 1—2 cm.

Micro: Finely crystalline, even-grained (calcite grains 5—15 μ), with abundant recrystallised, diffuse microcoquina, also fairly abundant larger fragments. Pyrite in small cubes. No glauconite observed. (Prep. 7769.)

Formation: Calcareous mud deposited in calm water together with varying quantity of argillaceous mud. Reducing environment.

Other beds of the Planilimbata limestone at Borghamn contain abundant glauconite grains and glauconite-impregnated corrosion-surfaces. An upper grey, glauconitic bed, 11 cm thick, has red-coloured portions and yellow corrosion-surfaces, i. e. a variegation recalling the equivalent rock in Öland, Västergötland, and Dalarna.

The Limbata limestone of Östergötland.

The Limbata zone of Östergötland, like that of several other areas, consists of thin-bedded, reddish-brown limestones, tinged grey and green at the bedding planes. The boundaries with the adjacent zones are indistinct.

Limbata limestone, Knivinge.

1. Lower part.

Macro: Bed 7 cm, with two corrosion-surfaces inside the bed. Immediately below these the limestone is dark-green and greyish-brown, downwards lighter brownish-grey, and above the following corrosion-surface pure grey. Winding worm-burrows, more faintly pigmented than surroundings. Bedding planes with green marl. (Rock specimen 6020).

Micro: Microcrystalline, even-grained (calcite grains approx. 10 μ), with glauconite and hematite pigment enriched on and beneath the corrosion-surfaces. Abundant microcoquina (0,02—0,2 mm); few large fragments (0,5—1,5 mm), mostly trilobites. No pelmatozoans observed. No pyrite or glauconite. (Prep. 7778 and 8899.)

Formation: Calcareous mud, mostly microcoquina, deposited in calm water. At times negative sedimentation and formation of corrosion-surfaces with glauconite. At times oxidizing environment.

2. Upper part.

Macro: Bed 5 cm, dense, dull, deep brownish-red with light-green portions, on bedding plane winding and uneven worm-trails. A few tabular barytes crystals in the green portions. No pyrite. (Rock specimen 6021.)

Micro: Finely crystalline, granular (calcite grains mostly 3—5 μ), with pigment of hematite dust, abundant but unevenly distributed. Microcoquina form a considerable part of the rock; they are recrystallized and difficult to distinguish from the fine-grained mass. Fragments of trilobites and pelmatozoans, the latter occasionally impregnated with hematite. Ostracods and small gastropods occur here and there. No pyrite or glauconite. (Prep. 7779.)

Diagenesis: Crystallization of mud and microcoquina; large calcite crystals in some shells. Formation of barytes crystals.

Formation: Calcareous mud deposited in calm water. Oxidizing environment. Local reduction through organic matter in trails and patches.

Limbata limestone, Borghamn. (1)

In the large quarry at Borghamn the Limbata limestone is well exposed in several beds of relatively great thickness. A number of the beds are of the same nature as

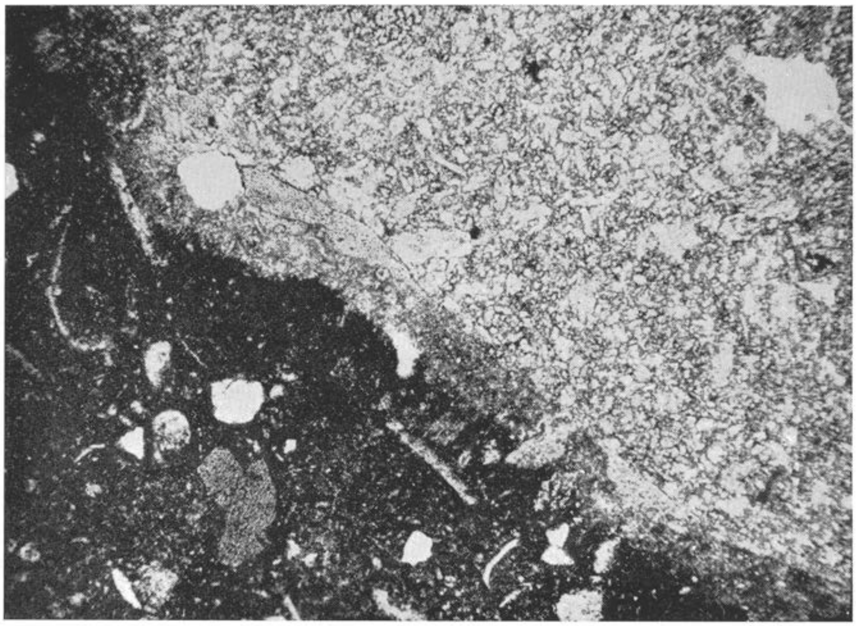

Fig. 117. Limbata limestone. Fragment limestone. Lower left: strongly pigmented, red and yellow, with grains of quartz (white) and glauconite (grey). Upper right: microcoquina. In the middle part band of glauconite. Lower Ordovician. Borghamn, Östergötland. (Prep. 7771 a, photo 1628.) — 33 ×.

the lower greyish-brown beds at Knivinge, and like these they exhibit beautiful corrosion-surfaces. In one bed a more irregular colour-banding was observed of red, yellow, and green, further disturbed by worm-burrows. An upper deep-red bed showed the following development:

Macro: Dense, brownish-red with green portions, which are irregularly reticulated towards the lower surface and bag-shaped with cylindrical cross-sections. These are corrosion-cavities, whose walls are coated with a crust of authigenic green glauconite. Immediately below the crust there is a yellowish-grey zone, which separates the corrosion-surface from the brownish-red mass.

Micro: Microcrystalline, granular (calcite grains 10—15 μ), strongly pigmented in the red and yellow portions. Abundant microcoquina, mostly crystallized and hazily bordered; larger fragments of trilobites, brachiopods, and pelmatozoans in smaller quantity. There are also fairly abundant grains of quartz, rounded, about 0,2 mm, and glauconite grains, 0,05—0,2 mm, the larger ones rounded and cracked.

The zonal structure in and around the cylindrical corrosion-cavities is the following (fig. 117):

1) Core, approx. 3 mm, strongly recrystallized microcoquina, often with crust of radiated calcite crystals. Glauconite and quartz in scattered small grains. Pigment

not noticeable, but glauconite is found in patches as thin infilling between calcite grains.

2) Band, 0,3 mm, impregnated with glauconite, here and there with a crust of compact glauconite. The calcite grains in the green band are rod-shaped and not orientated in any particular direction.

3) Strongly yellow-pigmented, microcrystalline zone, 0,2 mm, here and there almost black, outwards grading into normally developed zone 4.

4) Red-pigmented, fine-grained limestone with abundant quartz, glauconite, and fragments.

The lower part of the same bed is uniformly pigmented and contains negligible amounts of quartz and glauconite.

Diagenesis: Recrystallization of ground-mass with microcoquina.

Formation: Calcareous mud deposited in calm water, at times somewhat more agitated with transportation of quartz and glauconite grains. Oxidizing environment but with reducing elements and precipitation of authigenic glauconite on corrosion-surfaces.

Limbata limestone, Borghamn. (2)

Macro: Solid bed, divided into layers of 1,5—5 cm by uneven but largely parallel corrosion-surfaces. The rock is not cleavable along the corrosion-surfaces which are covered with authigenic glauconite. The colour is brownish-grey and grey with the brown-colouring strongest immediately below the corrosion-surfaces.

Micro: Major part microcrystalline (calcite grains 3—5 μ), with microcoquina and larger fragments in varying but relatively small quantities. Glauconite in a few small grains (approx. 0,1 mm). Pigment of argillaceous matter and hematite dust not very noticeable. At corrosion-surfaces a slight change in the size of the fragments. Often a faint yellow zone is found under the green glauconite coating in addition to the usual colour variation. Shells lying parallel to the corrosion-surface not infrequently form the corrosion boundary, whilst those at an angle stick up through the surface. There is no enrichment of the argillaceous matter, and the corrosion cannot, therefore, have been purely chemical (prep. 8770).

Diagenesis: Normal recrystallization.

Formation: Deposition in calm, shallow water.

The Asaphus limestone of Östergötland.

The Limbata limestone of Östergötland is overlain by a series of grey limestones, which Linnarsson and Tullberg (1882, p. 28) distinguished at Husbyfjöl (Västanå) as Heros and Expansus limestone. A few examples will be given here of the development of the limestone at another locality, Borghamn.

Asaphus limestone, Borghamn. (1)

Macro: Crystalline, glistening, grey. Bed 2—4 cm, with uneven, knobby bedding planes. Between these greyish-green marl.

Micro: Typical fragment limestone. Small portions microcrystalline (grains approx. 15 μ), otherwise the limestone is more distinctly crystalline (grains more than 0,5 mm). Profusion of fragments of trilobites, brachiopods, and pelmatozoans (fig. 118), often clearly worn and rounded pelmatozoans with faint impregnation of glauconite. The fragments are relatively large (often more than 2,5 mm). There are no grains of quartz or glauconite.

Diagenesis: Strong recrystallization of the matrix.

Formation: Clean-washed, worn, and rounded granular matter, consisting of fossil fragments, deposited in moving water.

Asaphus limestone, Borghamn. (2)

Macro: Crystalline, glistening, grey, with abundant large fragments of trilobites. Bed approx. 10 cm, with uneven bedding planes.

Micro: Typical fragment limestone. Crystalline, with clear calcite; only small portions fine-grained. Pelmatozoans particularly abundant; worn, rounded trilobite fragments common. A thin layer contains small, round, cryptocrystalline nodules (0,3—0,8 mm), occasionally with a shell fragment as core (fig. 119). They call to mind certain fine-grained types of limestone in Gotland, where small algal nodules give the rock a granular appearance (Hadding 1958).

Diagenesis and *formation*: As foregoing.

Expansus limestone, Kungs Norrby.

Macro: Dense, dull, greyish-green, marly, with whole carapaces of *Asaphus expansus*.

Micro: Marly micrococquina limestone with microcrystalline calcite and argillaceous pigment. Fragments of trilobites, pelmatozoans, ostracods, and brachiopods. Glauconite in a few small grains (0,02 mm). No quartz (prep. 8771).

Diagenesis: Slight crystallization of calcareous mud and microcoquina.

Formation: Deposition of calcareous and argillaceous mud in calm water. Neutral environment.

The Orthoceras limestone of Närke.

In Närke the Orthoceras limestone is readily accessible in quarries, at Lanna, Latorp, and Hällabrottet (formerly Yxhult), etc. The *Planilimbata limestone* has a thickness of about 3 m. The lower glauconitic part, approx. 0,3 m thick, rests directly upon Cambrian alum shale. The limestone is grey or reddish-grey with a few darker

Fig. 118. Pelmatozoan limestone. Asaphus limestone, Lower Ordovician. Borghamn, Östergötland. (Prep. 7772, photo 1587.) — 20×.

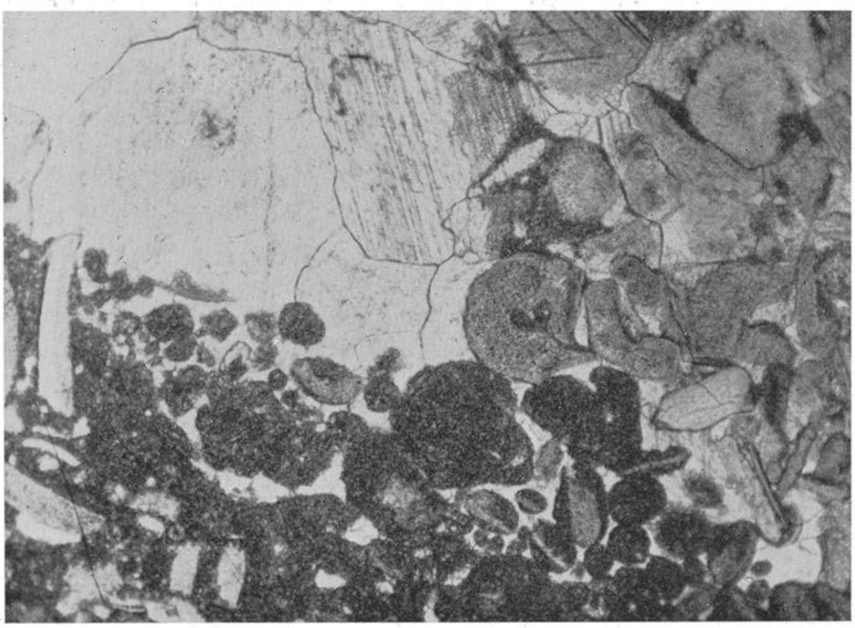

Fig. 119. Pelmatozoan limestone with crypto-crystalline (algal?) nodules. Asaphus limestone, Lower Ordovician. Borghamn, Östergötland. (Prep. 7774, photo 1687.) — 20×.

reddish-brown beds. Here and there are layers of greenish-grey shale. The *Limbata limestone* at Lanna is 9 m thick. The lowermost part, 1 m, is grey with a glauconite coating on corrosion-surfaces. A similar development is exhibited by the limestone in a few places higher up in the series of strata. Otherwise the Limbata limestone is variously reddish-brown, greyish-brown, and grey.

The Limbata limestone grades upwards into Asaphus limestone with *Asaphus expansus* etc. This limestone is partly marly, grey or greyish-green, and, like the equivalent limestone in Östergötland, rich in well-preserved trilobites. — The upper parts of the Asaphus series have not been observed in Närke.

For the Orthoceras limestone of Närke see especially TJERNVIK (1952 and 1956) and LINNARSSON (1875).

The Orthoceras limestone of Dalarna.

The basal bed of the Cambro-Silurian of Dalarna is a conglomerate, the Obolus conglomerate, which belongs to the Ceratopyge stage (HADDING 1932 and TJERNVIK 1956). Formerly, a layer of glauconitic sand and a few thin beds of glauconitic limestone were also reckoned as belonging to this stage. The following sedimentation shows a striking similarity to that which took place in other regions of Sweden which the invading sea reached long before Dalarna. One might have expected the Orthoceras limestone of Dalarna to be rich in quartz sand and other inorganic products of weathering, but it is just as poor in such admixtures as equivalent rocks in areas where the weathered pre-Cambrian bedrock had already been covered by thick sedimentary series before the deposition of Orthoceras limestone.

In the Orthoceras limestone of Dalarna there are in particular the following divisions and zones:

Divisions		Zones
Middle Ordovician	Upper grey	Schroeteri limestone
Lower Ordovician	Upper red	Platyurus limestone Gigas limestone (Transitional strata)
	Lower grey	Raniceps limestone Expansus limestone
	Lower red	Limbata limestone Planilimbata limestone

The boundaries between the different divisions and zones are indistinct in Dalarna as in other regions. Lithologically and paleontologically the transition takes place gradually, and we have reason to speak of transitional strata between them.

The Planilimbata limestone of Dalarna.

The lowermost beds of the Planilimbata zone consist of green limestones, which grade downwards into glauconitic limestone. The upper part of the zone consists of red limestones of the same lithological type as that we find in the Limbata zone. The greater part of the Planilimbata zone is occupied by variegated, red-yellow-green limestones. The zone is approx. 3 m thick at Sjurberg.

The series of strata at Sjurberg consists according to Warburg (1910) and Tjernvik (1956) of the following parts:

Sjurberg

<table>
<tr><th>Warburg 1910</th><th colspan="3">Tjernvik 1956</th></tr>
<tr><td>Limbata limestone 3,0 m</td><td colspan="2">Limbata limestone</td><td rowspan="5">Arenigian</td></tr>
<tr><td rowspan="2">Planilimbata limestone
3,08 m</td><td>Zone of Plesiomegal. estonica
Zone of Megalaspides dalecarlius</td><td>Upper Plani-limbata
limestone
1,65 m</td></tr>
<tr><td colspan="2">Zone of Plesiomegalaspis planilimbata 1,4 m</td></tr>
<tr><td>Ceratopyge limestone
0,14—0,16 m</td><td colspan="2" rowspan="2">Zone of Plesiomegalaspis armata and Lycophoria laevis 0,65 m</td></tr>
<tr><td>Glauconite sand 0,10 m</td></tr>
<tr><td>Obolus conglomerate
0,15—0,80 m</td><td colspan="3">Obolus conglomerate 0,15—0,80 m
(Tremadocian)</td></tr>
<tr><td colspan="4">Archaean granite</td></tr>
</table>

Planilimbata limestone, Sjurberg.[1]

Lower part.

Macro: Dense, light-green; no macroscopic glauconite grains. No macrofossils observed.

Micro: Finely crystalline, granular with the calcite grains (0,02—0,2 mm), round or ellipsoid, in a light, pale-green, submicroscopic argillaceous substance. There are no grains of glauconite or distinct fossil fragments. (Prep. 2655).

Diagenesis: Complete recrystallization of the sediment.

[1] A detailed description of the Planilimbata limestone at Sjurberg has been published by Tjernvik (1956, p. 165).

Fig. 120. Microcoquina limestone with glauconite grains. Planilimbata limestone, Lower Ordovician. Sjurberg, Dalarna. (Prep. 7211, photo 1646.) — 20 ×.

Formation: Microcoquina and calcareous mud deposited in calm, not littoral or altogether shallow water. Weakly reducing environment.

Upper part.

Macro: Dense, variegated (reddish-brown or greyish-yellow), with large, dark-green glauconite grains. Bed 8 cm. Bedding plane corroded with yellow zone and green glauconite-coating.

Micro: Microcrystalline, granular (calcite grains approx. 0,01 mm), abundant limonite pigment in the yellow portion. Microcoquina completely recrystallized. Larger shell fragments unequally recrystallized (fig. 120). Glauconite partly in the form of rounded or tabular grains (0,1—1,6 mm), partly as pigment in hazily circumscribed small lumps. No pyrite observed.

Diagenesis: Crystallization of calcareous mud and microcoquina.

Fromation: Calcareous mud with microcoquina, larger fragments, and glauconite grains deposited in slightly agitated water. Changing environmental conditions, at times oxidizing, at times neutral or reducing.

Planilimbata limestone, Skattungbyn. (1)

Macro: Dense, variegated (red-yellow) but for a large part lighter and darker brownish-red. Abundant pygidia of *Plesiomegalaspis planilimbata*.

Micro: Finely crystalline, even-grained, with varying content of pigment. Fragments, well-preserved, occur abundantly in the least pigmented parts of the rock, less frequently in the red portions. (Prep. 7826).

Formation: Deposition in calm water. Principally oxidizing environment.

Planilimbata limestone, Skattungbyn (2)

Macro: Bed 4 cm, with uneven bedding planes. Dense, variegated: yellow, red, and green. No macrofossils have been observed. No pyrite. Glauconite grains occur scattered throughout the rock and enriched locally. The different colours appear irregularly. Yellow, hazily bordered bands with uneven surfaces (corrosion-surfaces) are separated from reddish-brown portions, the latter with enriched grains of glauconite (allothigenic), by a one-millimetre-thick, clear-green (authigenic) glauconite-crust.

Micro: Crystalline-granular with calcite crystals of greatly varying size (0,01—0,4 mm) embedded in yellow or red pigment (fig. 4, p. 12). The pigment-content, like the grain-size, changes quickly in the limestone. No fossil fragments have been observed in the limestone.

Diagenesis: Completely recrystallized calcareous mud with obliteration of fossil fragments during formation of pure calcite crystals in ferrigenous dust.

The Limbata limestone of Dalarna.

(Lower red Orthoceras limestone)

The deep-red limestones which dominate the Limbata zone of Öland and Västergötland have their equivalent in the Lower red Orthoceras limestone of Dalarna. In several beds, however, the red colour is broken by irregularly running yellow bands, which appear together with distinct corrosion-surfaces, in the same way as in the Planilimbata limestone. At Sjurberg the Limbata limestone has a thickness of at least 3 m.

Lower red Orthoceras limestone, Fjäcka.

Macro: Dense, red with irregular, yellow bands beneath the corrosion-surfaces. The bed belongs to the lower part of the Limbata zone.

Micro: Microcrystalline, granular (calcite grains approx. 7 μ), with abundant micrococquina. Ostracods and trilobite fragments occur sparingly; no gastropods. In the red portions the hematite pigment is uniformly distributed; in the yellow bands the pigment is most enriched immediately beneath the corrosion-surfaces, which separate them from the overlying red portion (fig. 121).

Diagenesis: Faint recrystallization.

Formation: Calcareous mud deposited in oxidizing environment; shallow, at times calm, at times more agitated water with corrosion.

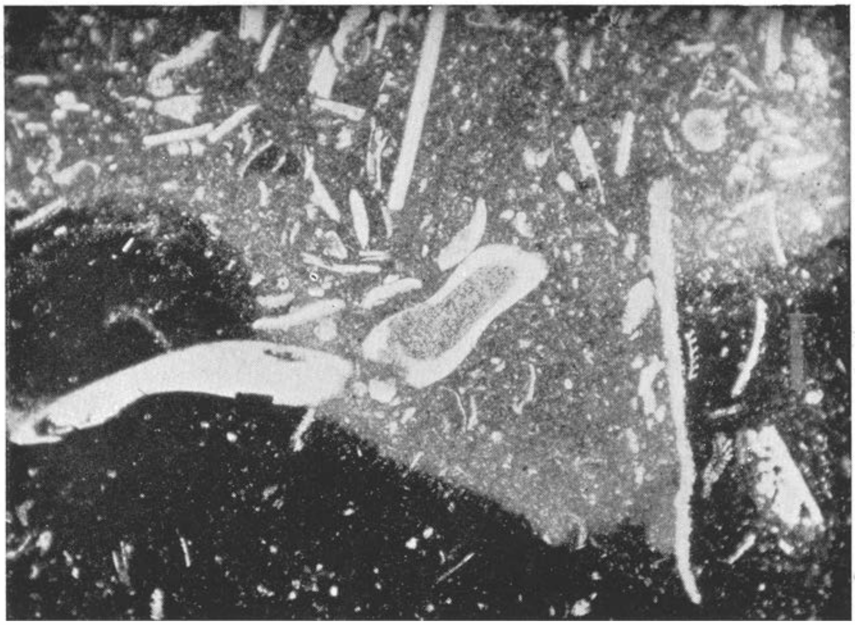

Fig. 121. Limbata limestone. Section through bed with corrosion surface. Lower part strongly pigmented, yellow, upper part slightly pigmented, pink, coarser grained. Lower Ordovician. Fjäcka, Dalarna. (Prep. 7313, photo 1690.) — 20 ×.

Lower red Orthoceras limestone, Dalarna.

(Törnquist's collection)

Macro: Dense, flamy brownish-red.

Micro: Finely crystalline microcoquina limestone with grains of varying coarseness. Small fragments of trilobites and ostracods occur abundantly, pelmatozoans more sparingly. No gastropods. The limestone is strongly but irregularly pigmented with hematite dust (fig. 122).

Diagenesis: Distinct recrystallization of mud and fragments.

Formation: Calcareous mud deposited in relatively calm and shallow water. Oxidizing environment.

Lower grey Orthoceras limestone in Dalarna.

The lower grey Orthoceras limestone of Dalarna has been thoroughly examined lithogenetically by Hessland (1949: II and IV), particularly with regard to the content of ooids (chamosite and limonite) and pseudo-ooids. Their formation with or without the assistance of algae has been elucidated by Hessland, who, in addition,

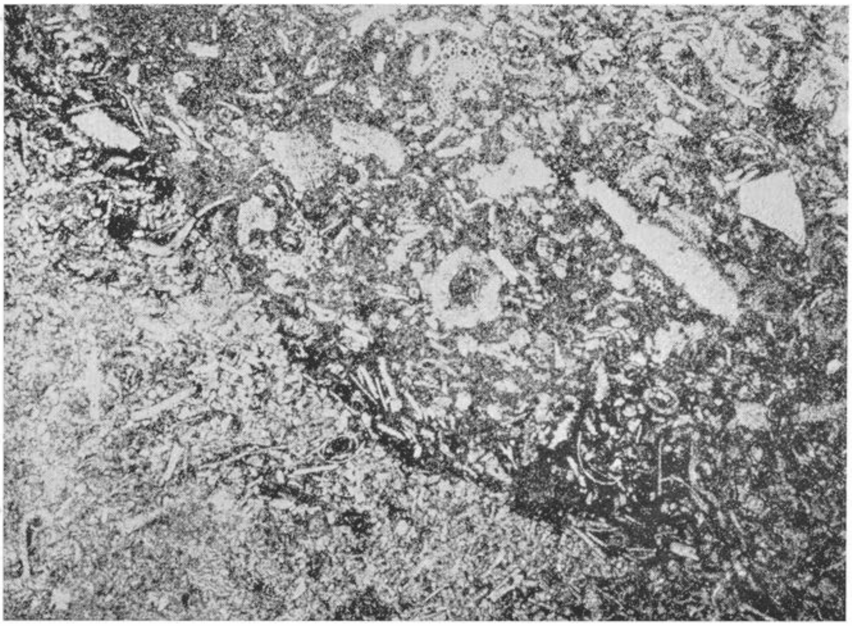

Fig. 122. Microcoquina limestone, irregularly pigmented. Limbata limestone. Dalarna. (Prep. 7197, photo 1360.) — 20×.

has had cause to discuss other conditions and problems concerning the rock and its formation.[1]

The lower grey Orthoceras limestone of Dalarna shows some similarity to the corresponding limestone in northern Öland. Like that it lacks a cystoid bed of the

[1] Hessland (1949, 1) in his work on Lower Ordovician ostracods of the Siljan district has given a short report on his observations of the general lithology of the Orthoceras limestone of the region. His report concerns the parts of the series of strata designated "lower red" (R_I), "lower grey" (G), and "upper red" (R_{II}) or broadly speaking Limbata, Expansus, Raniceps, and Gigas-Platyurus limestone. In a later work (1956, IV) Hessland has added to the report. A few data from Hessland's works will be given.

R_{II}. Upper red. (*Gigas-Platyurus limestone*)	Chestnut-brown with green patches and red coating on cephalopods. Trilobites, ostracods, cephalopods, crinoids. In the lower part boring algae. Ostracods are at a maximum in the lower part.
G. Lower grey.	*Raniceps limestone*: Abundant small gastropods, also ostracods, trilobites, crinoids. Abundant boring algae. Chamosite ooids. (Middle layer without gastropods and ostracods. Abundant ooids.) *Expansus limestone*: Abundant ostracods and in the lower part small gastropods. Crinoids. Ooids and in the lower part abundant glauconite grains. Boring algae, less frequent in the lower part.
R_I. Lower red. (*Limbata limestone*)	Reddish-brown with small, greyish-green patches and thin, irregular yellowish-brown bands, at the bottom bordered by a thin, greyish-green zone with grains of glauconite. Trilobites, ostracods, crinoids, and in the upper part abundant small gastropods. No algae.

type found both in southern Öland and Västergötland, but like the North-Ölandian limestone it can be divided into two zones: Expansus and Raniceps zones. The stratigraphical division has not been carried out, however. The rocks described below are called Expansus and Raniceps limestone according as they belong to the lower or upper part of the grey limestone.

At Kårgärde the lower grey Orthoceras limestone has a thickness of 1,8—3 m (according to TÖRNQUIST 1883, p. 37).

Expansus limestone, Utbyn, Rättvik. (1)

Macro: Crystalline, glistening, light grey, with large gastropods, brachiopods, and carapaces of trilobites (*Megalaspis grandis* SARS).

Micro: Limestone crowded with micrococquina and larger fragments (mostly 0,2—1 mm). Matrix crystalline, partly coarse-grained (fig. 123). Fragments mostly of trilobites and pelmatozoans. No small gastropods. Glauconite in a few grains (0,1 mm), phosphorite in small grains and as infilling or impregnation in porous fossil fragments. Pyrite in small aggregates.

Diagenesis: Irregular, partly strong crystallization of matrix.

Formation: Accumulated worn fragments. Deposition in shallow water. Weakly reducing environment. Partly slid sediment.

Expansus limestone, Utbyn, Rättvik. (2)

Macro: Dense, grey with dark-brown grains. Carapaces of *Megalaspis acuticauda* ANG.

Micro: Microcrystalline (grains 5—20 μ), irregularly pigmented, rich in worn, rounded fragments of trilobites, brachiopods, and pelmatozoans. Some of the fragments are impregnated with limonite and are occasionally quite opaque; others are filled with limonite in cavities and cracks (fig. 124). The origin of the limonite impregnation with the assistance of algae has been discussed in detail by HESSLAND (1949, II).

Diagenesis: Crystallization of the calcareous mud.

Formation: Deposition in shallow but relatively agitated water.

Expansus limestone, Boda.

Macro: Microcrystalline, dull, grey and greyish-brown. The colour variation is due to a varying admixture of argillaceous matter and brown grains. Numerous orthoceratites.

Micro: Crystalline (grains 5—50 μ), irregularly pigmented. Abundant fossil fragments, mostly smaller than 1 mm. Some are impregnated with limonite, others not, and they occur intermingled (fig. 125). The pigment fills the cavities and cracks

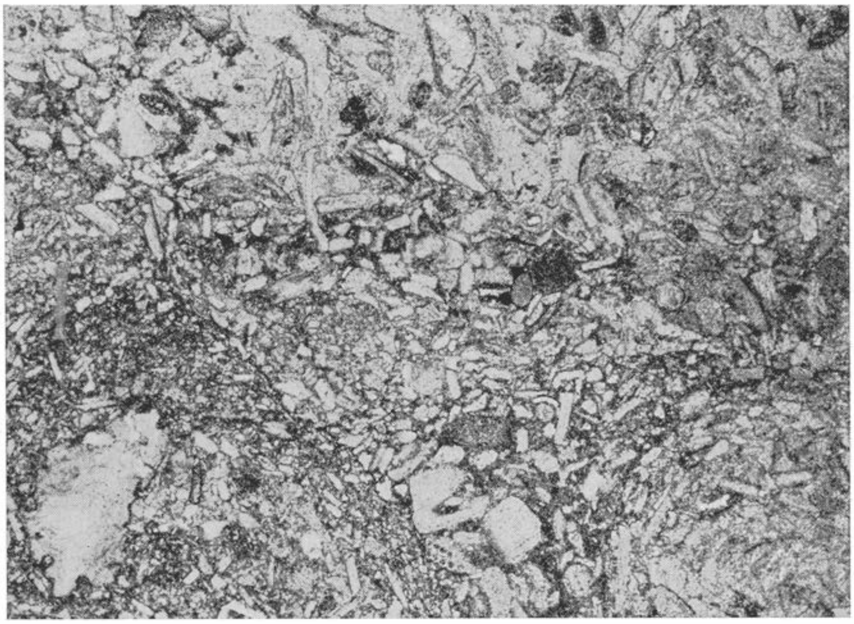

Fig. 123. Microcoquina limestone. Slid sediment (lower part). Expansus limestone. Lower Ordovician. Utbyn, Rättvik, Dalarna. (Prep. 7200, photo 1407.) — 20×.

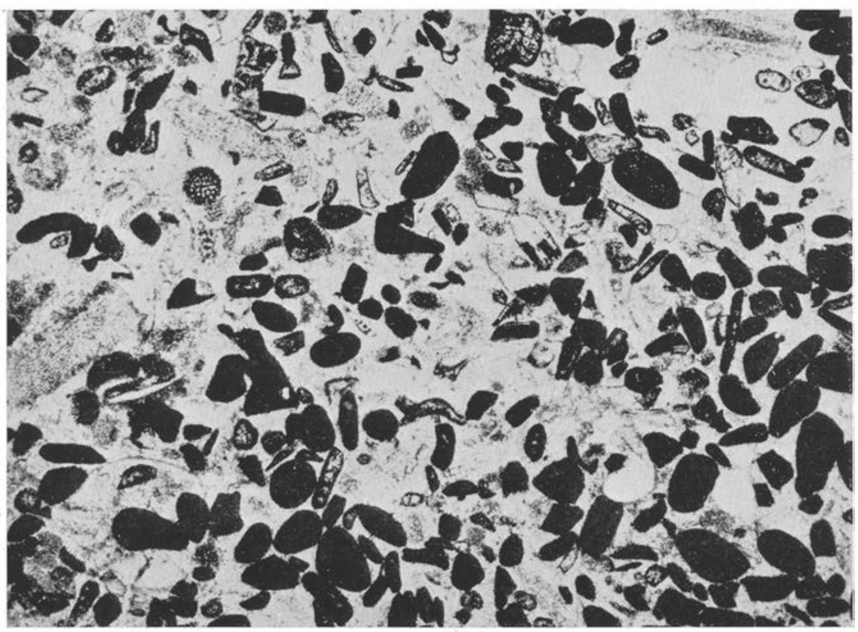

Fig. 124. Fragment limestone with ooids, pseudo-ooids and impregnations of limonite. Expansus limestone, Lower Ordovician. Utbyn, Rättvik, Dalarna. (Prep. 7198, photo 1361.) — 20×.

of the fragments. Limonite ooids have not been observed, but a crust of limonite is found on a good many fragments. Certain portions of the limestone are poor, others rich in pigmented grains.

Formation: As foregoing.

Raniceps limestone, Åberga, Orsa.

Macro: Microcrystalline, grey with certain portions tinged rust-brown. Scattered fragments of trilobites and large pygidium of *Megalaspis heros*.

Micro: Limestone with abundant microcoquina. Groundmass microcrystalline with irregularly disseminated argillaceous pigment. Ostracods and small gastropods are common. The fossil fragments are only pigmented in exceptional cases, but the gastropod shells are completely filled with limonite in one horizon of the bed (fig. 126). Embedded rounded fragments of dense limestone are strongly pigmented with limonite. No ooids, glauconite, or pyrite have been observed in the limestone.

Diagenesis: Crystallization of matrix and fragments.

Formation: Calcareous mud with fossil fragments deposited in shallow, gently moving water.

Gigas and Platyurus limestone in Dalarna.

Upper red Orthoceras limestone

The lower grey Orthoceras limestone of Dalarna is overlain by red limestone, which is usually called Gigas limestone. According to HESSLAND (1949, IV, p. 450), however, *Megalaspis gigas* does not occur until 5 m above the boundary between the lower grey and the upper red limestone. As I have no cause to go into stratigraphical problems but only intend to illustrate different rock types, I have treated the lower part of the upper red Orthoceras limestone as a unity, Gigas limestone, and called the upper part Platyurus limestone. The boundary between the Gigas and Platyrurus zones, however, is not more marked lithologically in Dalarna than in earlier mentioned regions.

The upper red Orthoceras limestone has a thickness of 9—12 m at Kårgärde (TÖRNQUIST 1883, p. 37).

Gigas limestone, Sollerön.

Macro: Dense, deep-red with greyish-green "clouds".

Micro: Microcoquina limestone with microcrystalline ground-mass, strongly but irregularly pigmented with hematite dust (fig. 127). Fragments of trilobites, brachiopods, some few pelmatozoans, and shells of ostracods and small gastropods.

Diagenesis: Faint recrystallization.

Formation: Deposition of calcareous mud in relatively calm water. Oxidizing environment.

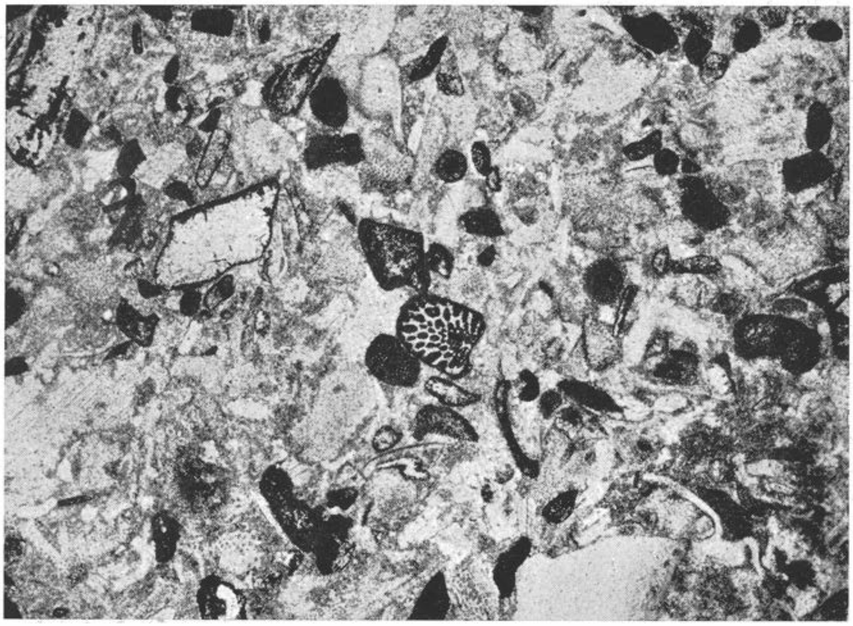

Fig. 125. Expansus limestone with irregularly pigmented fossil fragments. Lower Ordovician. Boda, Dalarna. (Prep. 7205, photo 1362.) — 20×.

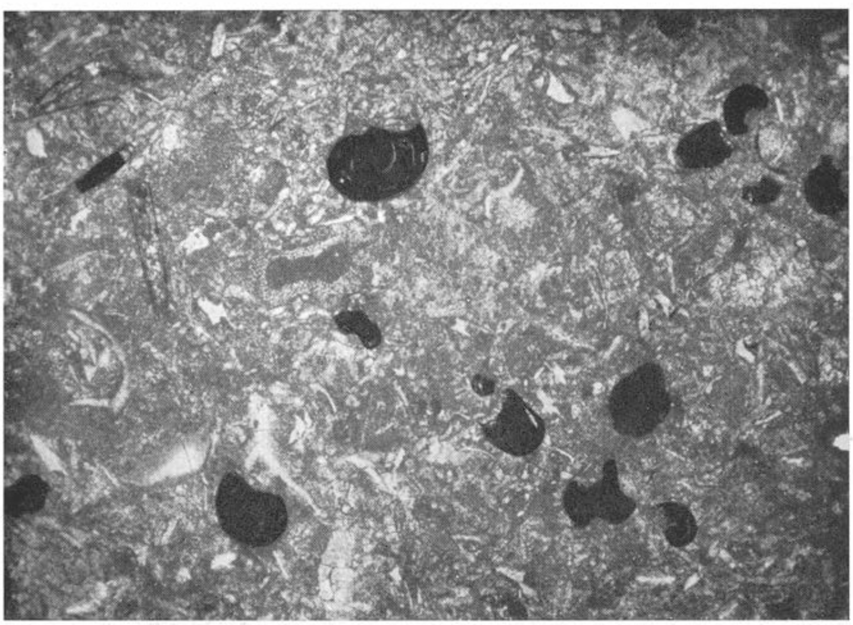

Fig. 126. Microcoquina limestone. Small gastropod shells filled with limonite. Raniceps limestone, Lower Ordovician. Åberga, Orsa, Dalarna. (Prep. 7827, photo 1647.) — 20×.

Fig. 127. Gigas limestone. Microcoquina limestone, irregularly pigmented with hematite. Lower Ordovician. Sollerön, Dalarna. (Prep. 7207, photo 1364.) — 20 ×.

Platyurus limestone, Sollerön.

Macro: Microcrystalline, deep-red with green flames. Orthoceratites and pygidia of trilobites (*Asaphus platyurus*).

Micro: Microcoquina limestone rich also in fossil fragments larger than 0,2 mm, pelmatozoans, ostracods, and small gastropods (fig. 128). Matrix finely crystalline with pigment of hematite dust. The gastropod shells are usually filled with limonite, and the pelmatozoans often somewhat impregnated with the same substance. No ooids.

Gigas-Platyurus limestone, Fjäcka, Boda parish.

The Gigas-Platyurus limestone at Fjäcka is a red microcoquina limestone of the same character as that mentioned above from Sollerön.[1] In the red limestone there is a grey bed, which is described below.

Macro: Dense, grey and, in the upper part, greyish-yellow.

Micro: Microcrystalline, granular (calcite crystals 5—10 μ). Microcoquina, recrystallized, in profusion. Shells of ostracods and small gastropods (fig. 129) and a few fragments of crinoids. Pyrite occurs in the rock in the form of small cubes (0,01

[1] The stratigraphy and lithology of the Platyurus limestone of Dalarna have been dealt with by JAANUSSON and MUTVEI (1953).

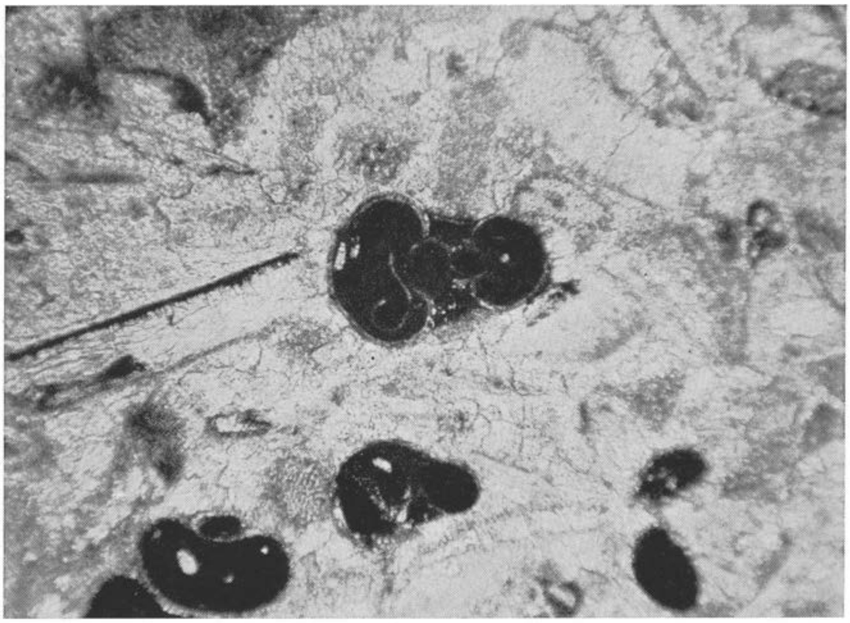

Fig. 128. Microcoquina limestone, strongly recrystallized. Platyurus limestone, Lower Ordovician. Sollerön, Dalarna. (Prep. 7208, photo 1463.) — 60×.

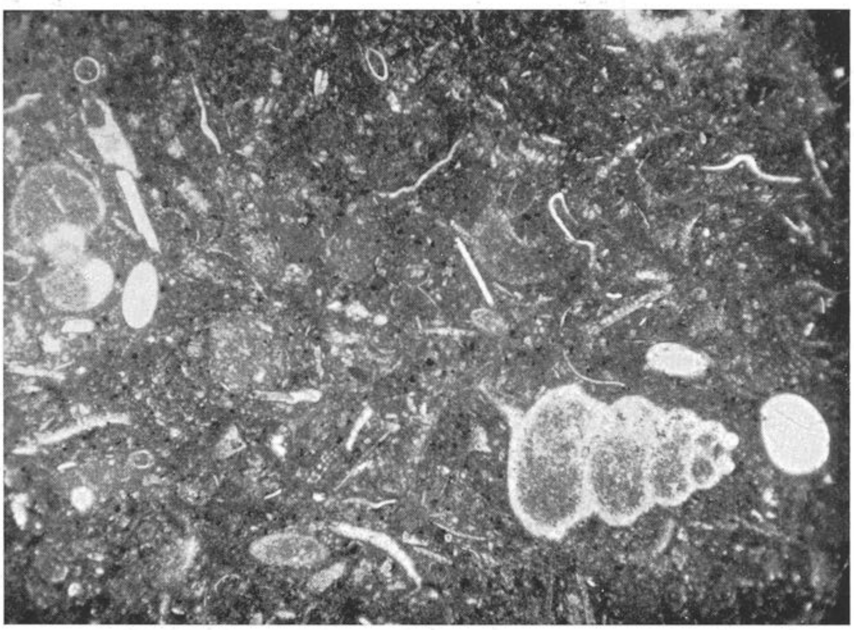

Fig. 129. Microcoquina limestone with small gastropods and ostracods. Upper red Orthoceras limestone. Fjäcka, Dalarna. (Prep. 7319, photo 1691.) — 20×.

mm) and not much larger, round aggregates. Weathered pyrite with a corona of limonite constitutes the colouring matter in the greyish-yellow part of the limestone.

Formation: All three limestones mentioned here from the upper red Orthoceras limestone of Dalarna have been deposited as calcareous mud in shallow and calm water. The grey in a typical reducing environment, the red in an oxidizing.

The Orthoceras limestone of Jämtland.

In the Storsjö region of Jämtland, which has been chosen here as a representative region, the Cambrian, Ordovician, and Silurian sedimentary series are relatively well preserved. Middle Cambrian and Upper Cambrian alum shales with anthraconites (at Brunflo, etc.) show that the subsidence of land was so considerable during Cambrian time that marine sediments must have been deposited throughout the region. The lithological development of the Cambrian sediments on the islands in lake Storsjön conforms closely with that found in Skåne. The same is true of the lowermost Ordovician strata. Glauconitic limestone and grey argillaceous shale with limestone beds belonging to the Planilimbata zone have been observed.[1] They are overlain in places, e. g. at Brunflo, by variegated limestones comprising Expansus, Gigas, Platyurus, and Schroeteri limestone. In other parts of the region, e. g. on Andersön, the limestone is partly replaced by black graptolite shale in the same way as in Skåne. Sedimentation took place largely without interruption during the deposition of the Orthoceras limestone, and there is nothing to suggest that a regression occurred either in the eastern region (Brunflo) or the more westerly (Andersön). Locally, however, there does occur an occasional peculiar feature in the otherwise normally developed series of strata (Lockne field).

Below, some of the rocks belonging to the Orthoceras limestone will be described.

Lower Ordovician limestone, Tossåsen.

The limestone, which contains *Lycophoria laevis* STANLEY etc., was formerly assigned to the Ceratopyge stage. According to TJERNVIK (1956, 169) it belongs to the Hunneberg group, Arenigian.

Macro: Dense, grey, brittle, with a few fragments of trilobites. The bedding plane is uneven, corroded, and covered with a thin crust of glauconite. Glauconite also occurs in scattered grains.

Micro: Even-grained, microcrystalline calcite (grains approx. 5 μ) with small (50—200 μ), completely recrystallized fossil fragments. Pyrite in scattered grains, 10—20 μ. (Prep. 7108).

Diagenesis: Recrystallization without formation of large calcite grains.

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[1] According to TJERNVIK (1956) the glauconitic rocks earlier reckoned as belonging to the Ceratopyge stage (Tremadocian) ought to be assigned to the Asaphus series (Arenigian).

Fig. 130. Microcoquina limestone. Coarseness varying. Planilimbata (?) limestone, Lower Ordovician. Brunflo, Jämtland. (Prep. 2093, photo 1656.) — 20 ×.

Formation: Calcareous mud deposited in relatively calm water and somewhat reducing environment. The consolidated mud has been corroded at times, the corroded surface later being covered with authigenic glauconite. The corrosion and the deposition of glauconite probably took place in connection with a lowering of the temperature of the water.

Planilimbata (?) limestone, Brunflo/Änge.

Macro: Dense, grey limestone with scattered fragments of trilobites and brachiopods.

Micro: Microcrystalline (grains 3—8 μ), in some portions rich in microcoquina (0,01—0,1 mm), which are completely recrystallized, in other parts an even-grained mass without distinguishable fragments (fig. 130). (This part undoubtedly consists of extremely finely divided, completely recrystallized fossil fragments.) Apart from the scattered fragments of trilobites the limestone has numerous cylindrical or slightly conical tubes with a diameter of 0,1—0,4 mm. An isolated fragment of a siliceous sponge has been noted. There is no glauconite, and pyrite occurs only sparingly in small cubes (20 μ).

Diagenesis: Complete recrystallization without formation of large crystals.

Formation: Fine calcareous mud deposited in relatively calm water and neutral or weakly reducing environment.

Expansus limestone, Sörgård, Brunflo.

The Expansus limestone is readily accessible in the quarry at Brunflo.

Macro: Dense, dark-grey, with glistening grains (crinoidal fragments). *Asaphus expansus* in complete specimens. Rust-weathered pyrite aggregates.

Micro: Micrococquina limestone. Ground-mass microcrystalline (grains approx. 10 μ) with argillaceous matter slightly enriched in narrow portions. The micrococquina are strongly corroded and recrystallized. Fragments of trilobites, brachiopods, and pelmatozoans, mostly smaller than 1 mm. Isolated fragments exhibit a black impregnation of iron sulphide. Green grains of glauconite (0,05 mm) have been observed in a few cases.

Formation: Calcareous mud deposited in calm water. Reducing environment. (Prep. 7143.)

Gigas limestone, Brunflo.

Macro: Dense, hard, dark greyish-brown with greyish-green portions and slickensides. Pygidia of *Megalaspis gigas.*

Micro: Micrococquina limestone (fig. 23, p. 44). Matrix microcrystalline (grains 5—10 μ). The micrococquina are strongly corroded. Large fragments of trilobites, brachiopods, ostracods, and pelmatozoans, many of them recrystallized. Scattered shells of small gastropods. Limonite as impregnation in a few pelmatozoans and as infilling in shells.

Formation: Calcareous mud deposited in calm water. Neutral environment, at times alternating, weakly reducing or weakly oxidizing.

Platyurus limestone, Brunflo.

Macro: Dense, faintly glistening, deep brownish-red with green patches. Bedding planes marly, red.

Micro: Micrococquina limestone. Ground-mass microcrystalline (grains approx. 5 μ), strongly but irregularly pigmented with hematite dust. Fragments of trilobites and pelmatozoans in the micrococquina. Shells of small gastropods and ostracods (fig. 131).

Orthoceras limestone, Andersön.

Black shales, Lower Didymograptus shale and Ogygiocaris shale, partly replace the Orthoceras limestone on Andersön. The strata are tilted and more or less metamorphosed. The limestone beds are lithologically uniform; they were sedimented as slightly bituminous, argillaceous calcareous mud. Only two types will be reported on here, one from the middle part, only negligibly metamorphosed, the other from the upper part, more thoroughly recrystallized.

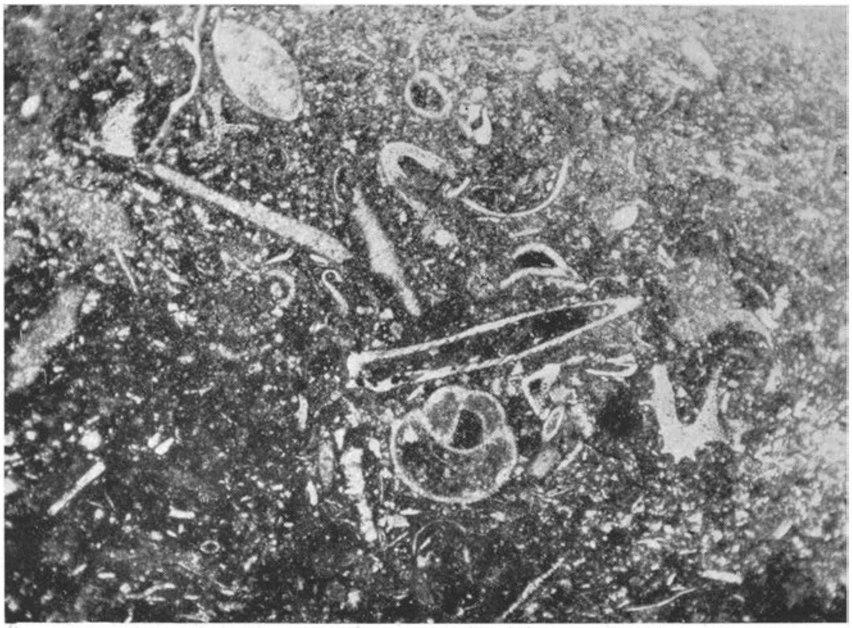

Fig. 131. Platyurus limestone. Microcoquina, hematite pigmented, with ostracods, gastropods and pelmatozoans. Lower Ordovician. Brunflo, Jämtland. (Prep. 7322, photo 1615.) — 20 ×.

Fig. 132. Platyurus limestone. Completely recrystallized fragment limestone. Lower Ordovician. Andersön, Jämtland. (Prep. 7088, photo 1616.) — 20 ×.

Limbata limestone, Andersön.

Macro: Dense, dull, black, with pygidia of *Megalaspis limbata.*

Micro: Microcoquina limestone. Microcrystalline (grains 5—10 μ), with irregularly distributed dark-brown pigment of bituminous matter. The fragments in the microcoquina are corroded and recrystallized. A few large fragments: trilobites, brachiopods, ostracods, and isolated pelmatozoans. No quartz grains. (Prep. 6632.)

Platyurus limestone, Andersön.

Macro: Dense, dark-grey with white veins of calcite. Pygidia of *Asaphus platyurus.*

Micro: Completely crystalline (grains 0,1—0,4 mm). Calcite aggregates with mosaic texture (fig. 132). Bituminous-argillaceous pigment between the grains. Quartz in isolated, angular grains (0,03 mm). Small fragments, which were no doubt present in the primarily deposited mud, have been obliterated during metamorphism of the rock. Only occasional large fragments of trilobites have been observed.

Formation: The Orthoceras limestone of Andersön has been formed by deposition of calcareous mud in calm water, not completely shallow or littoral. The appreciable bitumen-content indicates a reducing environment. The absence of pyrite in the beds investigated is worthy of note.

Platyurus limestone, Loke, Lockne field.

Macro: Dense, uniformly dark brownish-red.

Micro: Microcoquina limestone, rich also in fragments of 0,2—1 mm (fig. 133). Matrix fine-grained (approx. 5 μ), strongly pigmented with hematite dust. Ostracods, trilobite fragments, and less frequently pelmatozoans. No gastropods have been observed. (Bands of small round or slightly oval rings, 0,07 mm diameter. Free rings of the same type scattered throughout the rock. They occur in other localities, too.) Quartz in isolated small grains, 0,01 mm.

Diagenesis: Crystallization of the calcareous mud.

Formation: Calcareous mud and hematite dust deposited in calm water, not wholly shallow. Oxidizing environment.

Platyurus limestone, Öhntjärn, Tand.

Macro: Greyish-red, dense, with dessication cracks. No macrofossils observed.

Micro: Microcoquina limestone, microcrystalline (grains 5—50 μ), with trilobite fragments (0,04—0,2 mm). Shells of ostracods and small gastropod (fig. 134). A few crinoidal fragments. Iron-oxide pigment, enriched in certain parts as reddish-brown clouds. Pyrite crystals occur in very small quantity. A few glauconite grains (0,3 mm) with limonite-pigmented surface.

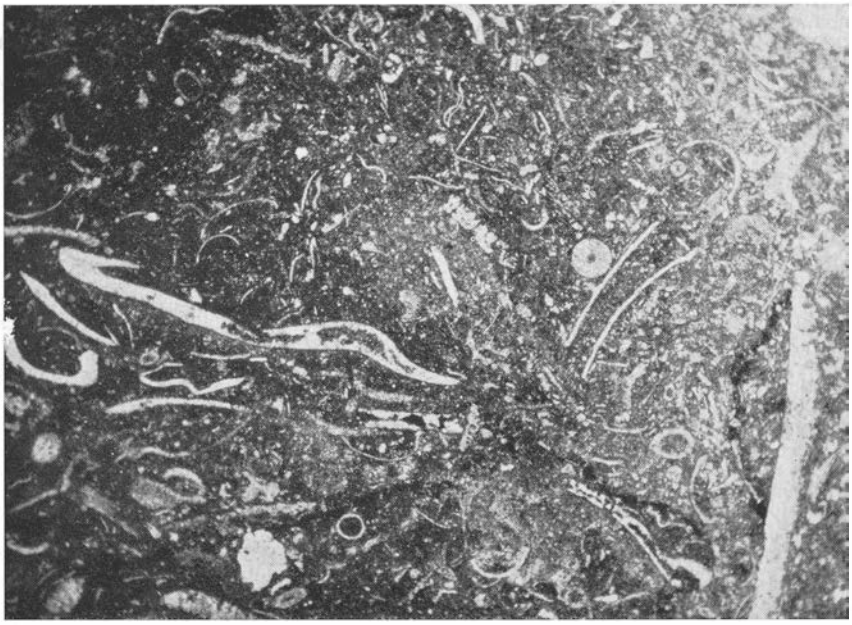

Fig. 133. Platyurus limestone. Microcoquina limestone, strongly pigmented with hematite dust. Lower Ordovician. Loke, Lockne, Jämtland. (Prep. 8773, photo 1619.) — 20×.

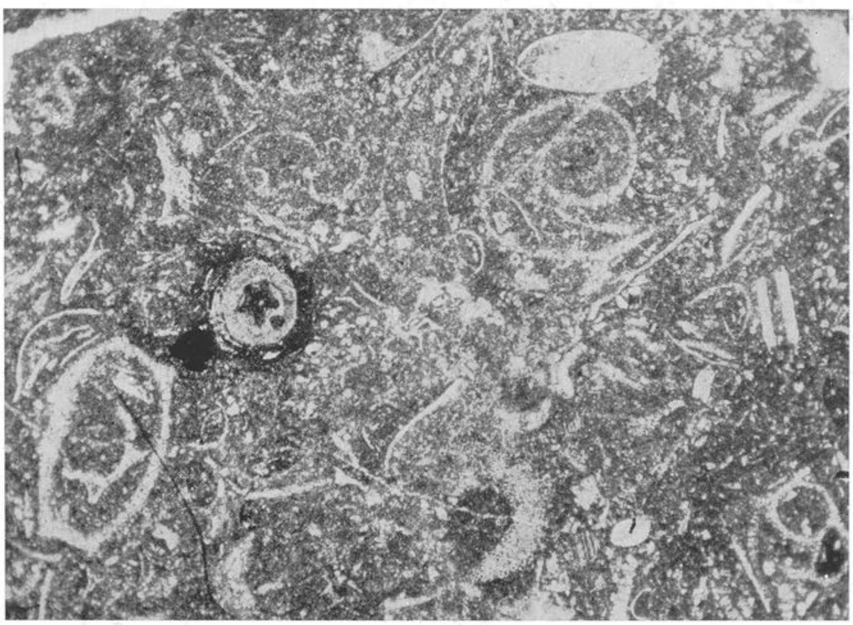

Fig. 134. Platyurus limestone. Microcoquina limestone with ostracods, gastropods and pelmatozoans. Lower Ordovician. Öhntjärn, Tand, Jämtland. (Prep. 2351, photo 1617.) — 20×.

Diagenesis: Faint recrystallization.

Formation: Calcareous mud deposited in calm, shallow water. Environment changing, largely neutral.

Orthoceras limestone, Lappgrubban, Lockne.

A normally bedded series of strata beneath the "Loftarstone" at Lappgrubban contains Orthoceras limestone of indeterminate age. Macrofossils have not been encountered. A typical specimen of the rock has been investigated.

Macro: Bed 4 cm, consists of dense, faintly glistening, dark-grey limestone with earthy, brownish-grey weathering crust.

Micro: Finely crystalline microcoquina limestone (grains approx. 5 μ) with abundant small fragments (0,1—0,5 mm) and a few somewhat larger trilobite fragments (fig. 135). Crinoidal stem disks (less than 1,5 mm) occur rather abundantly. Isolated small, green grains of glauconite.

Diagenesis: Faint crystallization.

Formation: Deposition of calcareous mud in relatively calm water. A slight bitumen-content indicates formation in reducing environment.

The Orthoceras limestone of Skåne.

The series of strata of the Asaphus series is as complete in Skåne as in Öland, but in contrast to the Ölandian, which is formed entirely of limestones, the Scanian is chiefly occupied by black graptolite shales.[1] In western Skåne (Fågelsång, Röstånga, etc.) only the Limbata zone and possibly the uppermost part of the Planilimbata zone are represented by limestone; in south-eastern Skåne and on the island of Bornholm (Denmark), however, the Lower Asaphus zone and the Schroeteri zone also show limestone facies. The Orthoceras limestone of Skåne is largely black or dark-grey and like the surrounding shales somewhat bituminous. The thickness is about 2 m at Fågelsång and twice as much in south-eastern Skåne. On Bornholm the thickness is about 5 m.

Limbata limestone, Fågelsång.

The lower bed of the quarry, locality 21a, Fågelsång, has numerous trilobites, e. g. *Cyclopyge* (*Aeglina*) *umbonata* (Ang.), and the bed belongs to the oldest part of the Limbata zone or the youngest part of the Planilimbata zone. On Bornholm it has been distinguished as Umbonata limestone.

Macro: Dense, black, with uneven, knobby bedding planes.

Micro: Microcoquina limestone, with fairly abundant large fragments (fig. 136). Matrix microcrystalline with varying grain-size, in certain parts less than 5 μ, in

[1] See scheme p. 100.

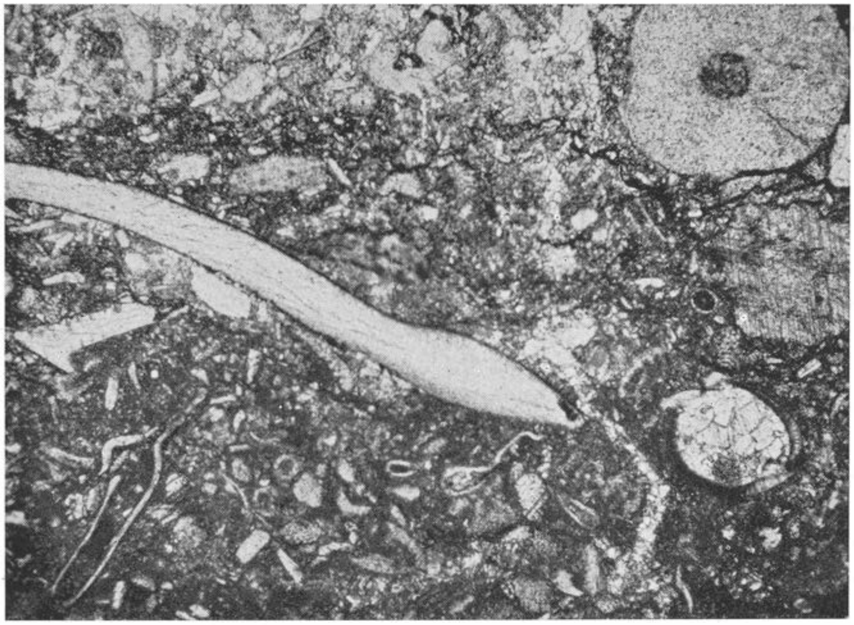

Fig. 135. Fragment limestone with trilobites, crinoids and microcoquina. Orthoceras limestone, Lower Ordovician. Lappgrubban, Lockne, Jämtland. (Prep. 7329, photo 1620.) — 20 ×.

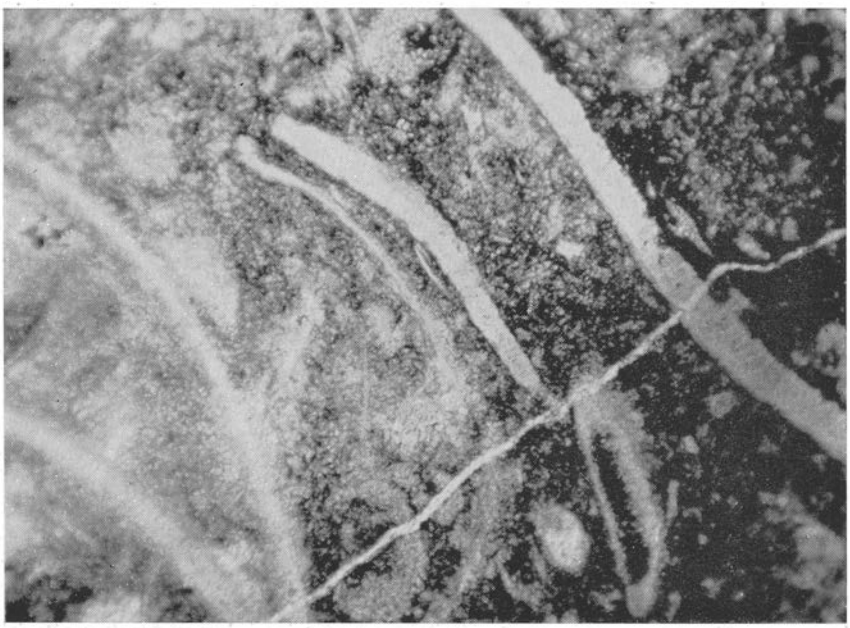

Fig. 136. Fragment limestone. Microcoquina completely recrystallized. Matrix bituminous. Orthoceras (Umbonata) limestone, Lower Ordovician. Fågelsång, Skåne. (Prep. 6581, photo 1318.) — 60 ×.

others 10—30 μ. The pigment, which is dark-brown and irregularly distributed, consists of bituminous argillaceous mud. The micrococquina are completely recrystallized, the larger fragments more or less corroded and recrystallized. In a few fossils there is an infilling of iron sulphide.

Diagenesis: Crystallization of the calcareous mud.

Formation: Deposition in calm not altogether shallow water. Reducing environment.

Upper bed of the quarry, locality 21a. Limbata limestone.

Macro: Dense, dull, black, with even bedding planes. Few macrofossils.

Micro: Microcrystalline, even-grained (calcite crystals approx. 5 μ), with a relatively uniformly distributed, dark-brown, bituminous pigment. Abundant microcoquina, crystallized and grading into the remaining calcite of the matrix. A few larger fragments (0,5—2 mm), mostly trilobites. Crinoids in isolated, very small stem disks (0,1 mm). No gastropods and only occasional ostracods. Radially fibrous calcite aggregates (0,03 mm) are not uncommon. No pyrite. (Prep. 7105.)

Diagenesis: Faint crystallization.

Formation: Calcareous mud with some argillaceous and organic matter deposited in calm, not altogether shallow water. Reducing environment.

In an upper bed, somewhat more argillaceous, there are a few completely recrystallized trilobite fragments but numerous micro-organisms, particularly smooth-shelled ostracods (0,1—0,4 mm), small gastropods (0,1 mm), and crinoid disks (0,1 mm). Scattered angular grains of quartz, 0,05 mm, throughout. (Prep. 6633.)

Limbata limestone, Tommarp.

Macro: Partly dense, black; partly finely crystalline, grey. Pygidium of *Megalaspis limbata*. A few small pyrite crystals.

Micro: (dense part) Fragment limestone. Matrix finely crystalline (grains 0,05 mm). Pigment dark-brown, bituminous, irregularly distributed. Microcoquina recrystallized and grading over into matrix calcite (fig. 137). Abundant large fragments of trilobites, ostracods, and to a less extent pelmatozoans. Glauconite in scattered small grains (0,2—0,3 mm). No pyrite observed. Dark, stylolite-like seams.

Formation: Calcareous mud with a small quantity of argillaceous and organic matter deposited in calm, relatively deep water.

Orthoceras limestone, Röstånga.

Macro: Glistening, microcrystalline limestone, black with earthy, brown weathering-skin. A few macrofossils (trilobite fragments, cystoid tests, *Sphaeronites*).

Micro: Fragment limestone with matrix of bitumen and calcite grains, the latter isometric and relatively uniform in size, 0,06 mm (fig. 138). Pelmatozoan fragments,

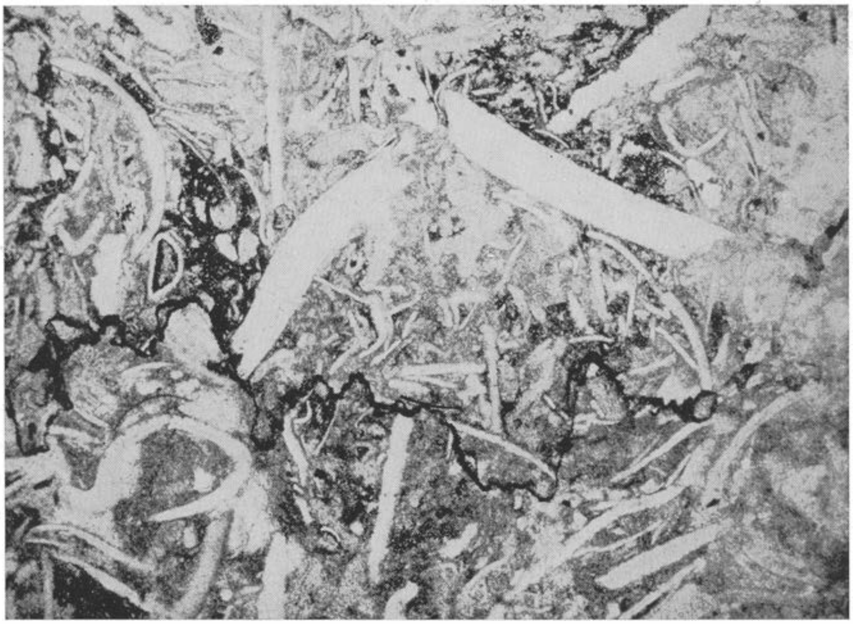

Fig. 137. Fragment limestone. Microcoquina recrystallized, grading over into matrix calcite. Limbata limestone, Lower Ordovician. Tommarp, Skåne. (Prep. 6541, photo 1305.) — 20 ×.

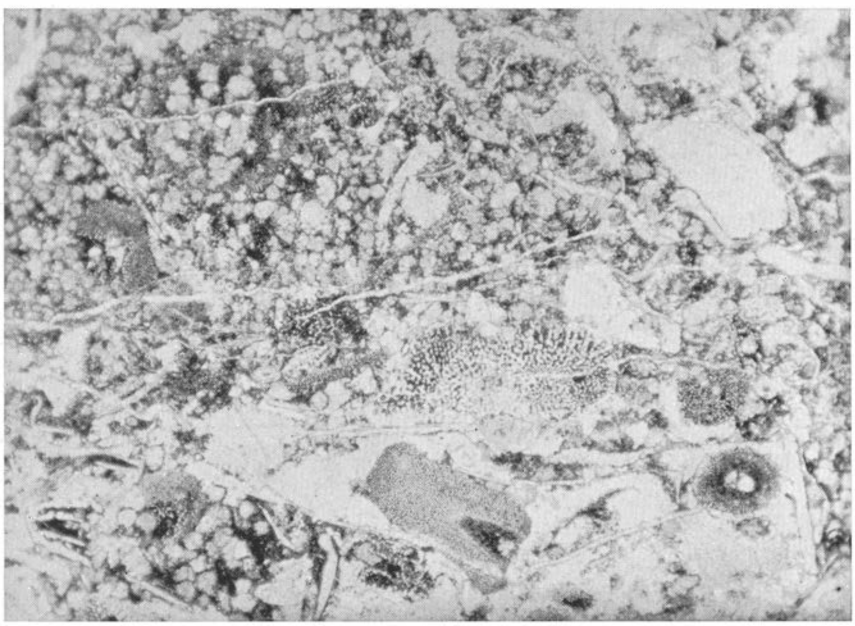

Fig. 138. Fragment limestone with pelmatozoans. Matrix of bitumen, argillaceous matter, and calcite grains. Orthoceras limestone, Lower Ordovician. Röstånga, Skåne. (Prep. 7103, photo 1692.) — 20 ×.

1—2 mm, occur especially profusely. They consist partly of cystoids, partly of crinoids. Pores in the fragments are filled with bitumen. Calcareous algae in small lumps with typical flocculent, cryptocrystalline texture. The fine-grained matrix calcite consists chiefly of completely recrystallized micrococquina. The individual small fragments can only be traced with difficulty, e. g. in crusts of radiated crystals. No pyrite, glauconite, or grains of quartz.

Diagenesis: Complete recrystallization.

Formation: Deposition of calcareous mud and fragments of pelmatozoans, trilobites, and (to a lesser extent) calcareous algae in water, at times calm, at times agitated. Reducing environment without deposition of iron sulphide.

The Orthoceras limestone of Bornholm (Denmark).

The Orthoceras limestone of Bornholm has been measured and investigated by POULSEN (1936). It has roughly the same thickness (5 m) and development as the corresponding rock in south-eastern Skåne. It also occupies the same stratigraphical position (Limbata limestone and lower part of the Lower Asaphus limestone). Thanks to POULSEN's investigation we know more about the occurrence of Orthoceras limestone on Bornholm than in Skåne, and it will therefore be mentioned here.

POULSEN's section covers the Orthoceras limestone of three places, Skelbro (Risebaek), Limensgade, and Vasagaard. The development is similar in these places, and the limestone is everywhere covered by a layer, at most 30 cm thick, of black shale with phosphatic nodules and pyrite concretions, in turn overlain by grey shale. The section has the following appearance:

(Uppermost)	Grey shale	160 cm	
	Phosphorite conglomerate in phosphoritic shale with pyrite concretions	30 »	
	Limestone, thick-bedded	280 »	Orthoceras limestone 490 cm
	Limestone, thin-bedded, alternating with shale	80 »	
	Limestone, homogeneous bed	100 »	
	Limestone, glauconitic with phosphorite	30 »	
	Phosphorite conglomerate with glauconite on stratified phosphorite	12 »	

The Orthoceras limestone at Risebaek has been described by NÖRREGAARD (1908), and the present writer has studied it in all the three places mentioned above. Development in the three localities agrees both macroscopically and microscopically.

Orthoceras limestone, Risebaek, Bornholm (Denmark).

Lower part, "Umbonata limestone".

Macro: Dense, hard, uniformly light-grey limestone. In the upper part of the bed scattered dark grains of glauconite, isolated fragments of phosphatic nodules

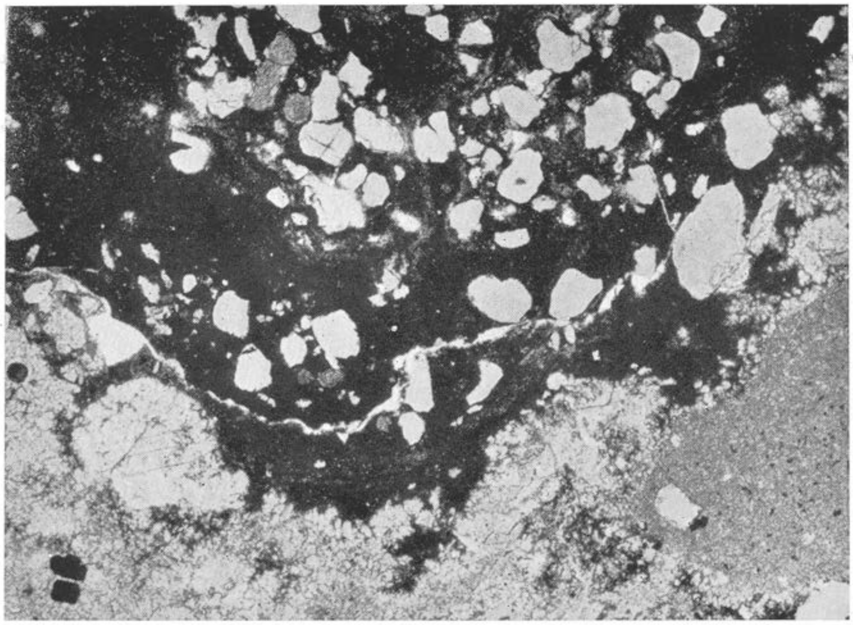

Fig. 139. Bituminous and phosphatic substance with grains of glauconite (white) on micro-crystalline fragment limestone. Orthoceras (Umbonata) limestone, Lower Ordovician. Risebaek, Bornholm. (Prep. 6565, photo 1468.) — 20×.

(1—5 mm), and small pyrite crystals. The upper bedding plane shows shallow, cup-shaped depressions separated by an irregular network of ridges. The depressions are filled with a black mass containing grains of glauconite.[1]

Micro: The matrix of the limestone consists of crystalline calcite (grains 3—10 μ) with distinct microcoquina. Only a few larger trilobite fragments are found, all recrystallized and hazily circumscribed. The glauconite grains (0,3 mm) are clear green. Peripherally they are often replaced by calcite, but the dark coating which primarily covered the grains is preserved even in cases where complete metasomatism has taken place (cf. Hadding 1932, p. 101 etc.). The phosphorite is dense, brown in transmitted light, and isotropic. Pyrite occurs in small, scattered cubes.

The filling of the depressions on the bedding plane consists of a dense, dark-brown, isotropic substance (bituminous and phosphatic) with intercalated glauconite grains, phosphorite fragments, and fibrous aggregates of chalcedony (fig. 139).

---

[1] Concerning the development of the bedding planes Deecke (1877, 6) wrote: "Die Schichtflächen des Kalkes sind uneben, mit Wülsten bedeckt, die man als Ausfüllung von Austrocknungsrissen deuten könnte; oder sie machen den Eindruck, als ob die Grenzfläche von Kalk und Schiefer unregelmässig verliefe und der plastische Kalkschlamm durch Nachsetzen der Thone in diese eingedrungen sei."

Nörregaard (1908) and Grönwall (1916, 73) interpret the ridges and depressions of the rock as dessication-fissures or corrosion-pits.

Diagenesis: Complete recrystallization of the calcareous mud.

Formation: Deposition took place in the following stages: 1) Calcareous mud without admixture of coarse grains was deposited in quiet, shallow water. 2) Through a gradually increased turbulence in the water the partly consolidated sediment was subjected to corrosion. 3) Glauconite, phosphorite, and siliceous sponges were deposited in the corrosion-pits.[1]

Orthoceras limestone, Risebaek, Bornholm (Denmark).

Upper part.

Macro: Bed more than 7 cm thick. Dense, hard, splintery, light-grey, with relatively even, marly bedding planes. Thin, small trilobite fragments occur sparingly.

Micro: The matrix consists of microcrystalline calcite (grains approx. 5 μ), with numerous recrystallized, very small fragments difficult to distinguish from the granular calcite. Fragments of trilobites (1—2 mm) occur thinly scattered. Quartz and glauconite in a few grains (0,01 mm), pyrite rather more generally. Pigment of argillaceous matter (prep. 6566).

Diagenesis: Complete recrystallization of calcareous mud, including microcoquina.

Formation: Deposition of calcareous mud in quiet water, somewhat deeper than that in which the lower beds were formed. Neutral environment.

Orthoceras limestone, Limensgade, Bornholm.

Macro: Bed 3 cm, with uneven bedding planes. Dense, hard, dark-grey limestone with black, irregular lenses and patches. Weathering-crust light greyish-brown.

Micro: Microcrystalline matrix (grains approx. 5 μ) with brown, irregularly distributed pigment of bitumen. The rock consists for a large part of microcoquina, completely recrystallized and blending into the microcrystalline calcite aggregate. Larger fragments (0,2—2,0 mm) occur throughout. There are no crinoids. Pyrite in small grains, weathered to limonite, which colours the surrounding calcite aggregate (prep. 6554).

Diagenesis: Complete recrystallization.

Formation: Calcareous mud deposited in quiet water, not close to land. Reducing environment.

Middle Ordovician Limestones.

At present stratigraphers seem generally to want to draw the lower boundary of the Middle Ordovician between the Platyurus-Gigas limestone and the Schroeteri limestone or, where a graptolite facies is predominant, between the Upper Didymo-

[1] Deecke pointed out (1897, 6) the presence of sponge-spicules of chalcedony.

<table>
<tr><th></th><th>Skåne</th><th>Öland</th><th>Västergötland</th><th>Dalarna</th><th>Jämtland</th></tr>
<tr><td rowspan="2">Upper Ordovician</td><td rowspan="2">Zone with Pleurograptus linearis</td><td rowspan="2">Masur limestone</td><td rowspan="2">Tretaspis shale</td><td colspan="2">Black Tretaspis shale</td></tr>
<tr><td>Masur limestone</td><td>Masur limestone</td></tr>
<tr><td rowspan="6">Middle Ordovician</td><td>Z.w. Dicranograptus clingani</td><td rowspan="3">Macrourus limestone</td><td rowspan="3">Shale
Chasmops limestone w. metabentonite
Shale</td><td rowspan="3">Macrourus limestone (“Bryozoan limestone”)</td><td rowspan="3">Upper Chasmops limestone</td></tr>
<tr><td>Z.w. Amplexograptus vasae</td></tr>
<tr><td>Z.w. Diplograptus molestus</td></tr>
<tr><td>Z.w. Nemagraptus gracilis</td><td>Ludibundus limestone (Echinosphaerites limest.)</td><td>Ludibundus limestone</td><td>Ludibundus limestone (“Cystoidean limestone”)</td><td>(Ludibundus) Lower Chasmops limestone
“Loftarstone” conglomerate</td></tr>
<tr><td>Z.w. Climacograptus haddingi (Bronni limestone)</td><td>Crassicauda limestone</td><td>Crassicauda limestone</td><td>Crassicauda limestone (“Flagkalk”)</td><td>(Hiatus?)</td></tr>
<tr><td>Z.w. Glossograptus hincksi</td><td>Schroeteri limestone</td><td>Schroeteri limestone and shale</td><td>Schroeteri limestone</td><td>Ogygiocaris shale and Schroeteri limestone</td></tr>
<tr><td>Lower Ordovician</td><td>Upper Didymograptus shale</td><td>Platyurus-Gigas limestone</td><td>Platyurus-Gigas limestone</td><td>Platyurus-Gigas limestone</td><td>Platyurus-Gigas limestone</td></tr>
</table>

graptus shale and the Lower Dicellograptus shale (the zone with *Glossograptus hincksi*). The upper boundary is drawn between the Macrourus limestone and the Masur limestone or, with a graptolite facies, between the zone with *Dicranograptus clingani* and the zone with *Pleurograptus linearis* (see scheme above). In addition to the rocks which were earlier reckoned with the Chasmops stage, the following have been transferred to the Middle Ordovician: the Schroeteri limestone, which was formerly regarded as the youngest part of the Asaphus series (Orthoceras limestone), and of the graptolite facies the Lower Dicellograptus shale. Correlation of the zones into series with limestone facies and with shale facies has gained in clarity from the investigations of the last few years, even if certain points still remain to be cleared up.

The Middle Ordovician limestones show great variations, and they occur in several places in lenticular or uneven beds and with a high content of argillaceous material.

Below will be traced the variations in the Middle Ordovician rocks of the more important sedimentary areas. Regional development will be discussed in a later survey.

The Middle Ordovician limestones of Dalarna.

As can be seen from the scheme on page 184, all the Middle Ordovician zones of Dalarna are represented by limestones. These are relatively readily accessible, and they have also long been subjects of interest for geologists, especially paleontologists. Their lithological nature and formation will be illustrated and discussed below, where they will be dealt with in order of age starting from the basal zone of the series of strata, the Schroeteri limestone. There is no sharp boundary between the various subdivisions. Thus the boundary between the Schroeteri limestone and the overlying Crassicauda limestone ("Flagkalk") is not established. Between the latter limestone and the Lower Chasmops limestone (Ludibundus limestone) transition occurs without noticeable lithologic change (JAANUSSON 1947, p. 47). The Upper Chasmops limestone (Macrourus limestone) is only accessible in a section at Fjäcka, but "as the rocks of the section (the excavated parts of which are 0,3—1 m high) are unevenly and in parts intensely weathered, the details of several beds and contacts are not quite cleared up" (JAANUSSON and MARTNA 1948, p. 185).

Schroeteri limestone, Kårgärde, Orsa.

Macro: Dense, hard, dark-grey limestone with *Illaenus schroeteri* and white discs of crinoid stems.

Micro: Microcoquina limestone, with abundant coarser fragments (fig. 140). Matrix microcrystalline with grains of varying size (mostly 5—10 μ), grading over into crystallized microcoquina (<0,2 mm) and trilobite fragments (mostly 0,5—2 mm). Pigment, partly dark-brown (limonite), enriched in certain fossils (ostracods, gastropods, and pelmatozoans), partly grey (argillaceous), uniformly distributed, and hardly noticeable under the microscope.

Diagenesis: Crystallization of the calcareous mud and fragments.

Formation: Calcareous mud with fragments deposited in quiet, not altogether shallow water. Neutral environment.

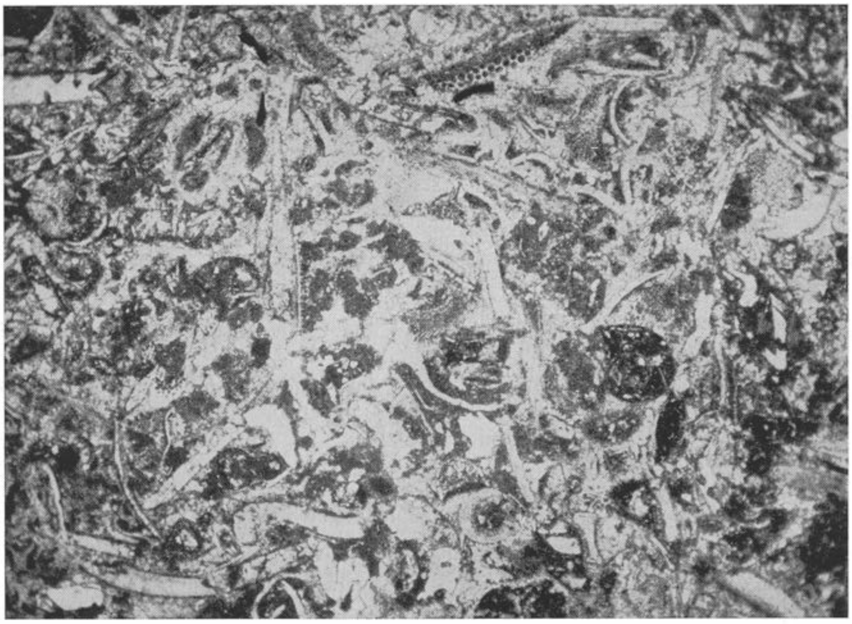

Fig. 140. Fragment limestone with microcoquina. Schroeteri limestone, Middle Ordovician. Kårgärde, Dalarna. (Prep. 8774, photo 1649.) — 20×.

Schroeteri limestone, Fjäcka.

Macro: Dense, dull, grey limestone with greenish-grey parts, hard with softer, marly portions. The rock is possibly a transitional type to Crassicauda limestone.

Micro: Cryptocrystalline, highly pigmented limestone with microcoquina (grains approx. 20 μ) and somewhat larger fragments (0,5—2 mm) of trilobites, ostracods, gastropods, and pelmatozoans. (Prep. 7309).

Diagenesis: Recrystallization of the fossils noticeable; ground-mass without microscopically evident crystallization.

Formation: Deposition in quiet water. Neutral environment or weakly reducing.

The Crassicauda limestone of Dalarna.

"Flagkalk" (Calcareous flagstone).

Törnquist (1883) has described the occurrence of "Flagkalk" in several places in Dalarna, e. g. Kårgärde and Fjäcka. He gives the following section from Kårgärde:

Bryozoan limestone and marl		
Cystoidean limestone		approx. 17 m
Gnarled, knobby limestone Thick-stratified limestone Light, cracked limestone	"Flagkalk"	approx. 7,5 m

Upper grey Orthoceras limestone	approx. 4 m
Upper red Orthoceras limestone	approx. 10 m

The limestone is now less easily accessible at Kårgärde, and the intensely weathered rock is uniform, marly.

An investigation of the limestone was made by JAANUSSON (1947) in which the section at Fjäcka was cleaned up. No division of the limestone into lithologically different parts seems to have been made. The rock is described as follows (JAANUSSON 1947, p. 45): "Der Flagkalk besteht aus kryptokristallinischen, ton- und fragmentreichen, stellenweise organodetritischen, blaugrauen Kalksteinen mit mergeligen bis schiefrigen Zwischenlagen. Infolge der unregelmässigen Verteilung des Tonbestandteiles sieht der Kalkstein bei stärkerer Verwitterung gewissermassen knollig aus. Charakteristisch für die Kalksteine des Flagkalkes in Dalarna ist das häufige Vorkommen von langen, schwarzen, 2—6 mm breiten Lebensspuren, die stellenweise eine Verzweigung aufweisen. Ähnliche Lebensspuren wurden auch im unteren Chasmopskalk gefunden". The name "flagkalk", JAANUSSON (1947, 46) suggests, should be replaced by "Kalkstein mit *Illaenus crassicauda* und *Tallinnella dimorpha* oder Crassicauda-Stufe".

Crassicauda limestone, Fjäcka.

"Flagkalk".

Macro: Light grey or greenish-grey, dense, hard limestone in the form of lenses or lumps, surrounded by flaking (through weathering), greyish-green marlstone. Small fossil fragments occur abundantly in the rock and make it rough or granular to the touch (especially when weathered).

Micro: Microcrystalline (grains approx. 5 μ), strongly argillaceous, rich in microcoquina (approx. 20 μ) and small fragments of trilobites and pelmatozoans (0,2—1,0 mm). Larger fragments occur more sparsely (fig. 141).

Diagenesis: Slight recrystallization.

Formation: Calcareous and argillaceous mud deposited in quiet water and neutral environment.

Ludibundus limestone, Fjäcka.

"Cystidékalk" — Lower Chasmops limestone.

In the marly limestone series, which occupies practically the whole Middle Ordovician of Dalarna, there is a section with beds rich in cystoids. Without definitely delimiting this part of the series of strata TÖRNQUIST distinguished this rock with the term "cystidékalk" (cystoidean limestone). The cystoids only occur, however, in a minor part of the series of strata. As index-fossil for this JAANUSSON (1951) has instead mentioned *Asaphus ludibundus* TÖRNQ., for which reason and with full justification he introduces the term "Ludibundus limestone", a term analogous with "Crassicauda limestone" and "Macrourus limestone" for the underlying and overlying beds with *Illaenus crassicauda* WAHLB. and *Chasmops macrourus* SJÖGR.

Fig. 141. Argillaceous fragment limestone with pelmatozoans. Crassicauda limestone ("Flagkalk"), Middle Ordovician. Fjäcka, Dalarna. (Prep. 7302, photo 1650.) — 20×.

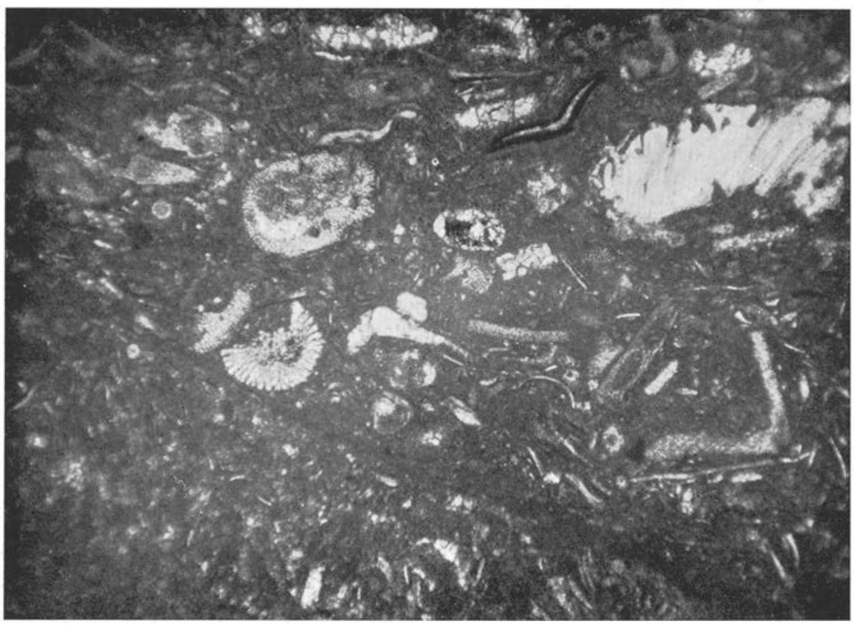

Fig. 142. Argillaceous microcoquina limestone. Ludibundus (Cystoidean) limestone, Middle Ordovician. Fjäcka, Dalarna. (Prep. 7321, photo 1764.) — 20×.

Like the Crassicauda and the Macrourus limestones the Ludibundus limestone consists of solid beds and lenses or lumps surrounded by highly porous (on weathering), marly limestone. The fossil content varies; the macrofossils are fairly well preserved. From a lithological point of view the series of strata is uniform; the samples examined have all the same character.

Macro: Dense, hard, greyish-green limestone in lumps and lenses surrounded by greyish-green, loose (weathered), marly limestone.

Micro: Ground-mass microcrystalline (grains mostly 5—10 μ), with abundant microcoquina (approx. 20 μ) and small fragments (fig. 142). A few larger fragments. Besides pelmatozoans, trilobites, and ostracods, occasional small gastropods occur, too. Grey, cryptocrystalline, argillaceous pigment surrounds the calcite grains.

Diagenesis: Slight recrystallization.

Formation: Sediment deposited in quiet water and neutral environment.

With the Lower Chasmops limestone Jaanusson and Martna (1948, 189) reckon, too, a series about 5 m thick of argillaceous, grey limestone with beds of plastic clay (probably bentonite), which underlies the Macrourus limestone.

Macrourus limestone, Dalarna.

"Bryozoan limestone" — Upper Chasmops limestone.

The youngest part of the Chasmops series, the Macrourus limestone, consists of limestone beds separated by marly layers. The series of strata, which has been estimated at 9 m, contains bryozoans, according to Törnquist (1883, p. 20), and was named by him "bryozoan limestone".

In the samples of Macrourus limestone examined nothing was observed to distinguish this limestone and Ludibundus limestone from a lithological point of view. In the field, too, they grade over into one another. The upper part of the series contains thicker marly layers than other parts of the Chasmops stage.

The following notes were made on samples of Macrourus limestone from Fjäcka:

Macro: Beds 2—3 cm; dense, grey, hard limestone with marly bedding planes.[1]

Micro: Ground-mass microcrystalline (grains $<10\ \mu$), argillaceous. Abundant microcoquina (0,02—0,2 mm) and small fragments (<1 mm). Bivalves (ostracods) with shells less than 0,5 mm, spherical tests of approx. 1 mm diameter (foraminifera?), and other plankton organisms occur distributed throughout the sediment. Pyrite occurs sparingly in small crystals and aggregates. (Prep. 7304).

Diagenesis: Slight recrystallization.

Formation: Calcareous and argillaceous mud deposited in quiet water. Neutral or weakly reducing environment.

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[1] Regarding the marly layers Jaanusson and Martna (1948, 188) say: "The calcareous shale between the limestone layers is greyish-green, soft and contains small grains of glauconite."

The Middle Ordovician limestones of Västergötland.

Formerly the Middle Ordovician of Västergötland was only known in its main features, and both paleontologically and lithologically the series of strata still offers a little investigated field of study. After identification of the light, soft argillaceous layers in the upper part of the series of strata as bentonite (THORSLUND 1945), core-drillings and excavations were undertaken, which have contributed to an increase in our knowledge of the rocks. (See WAERN, THORSLUND, and HENNINGSMOEN 1948.)

The series is rich in calcareous sediments. The lowermost part, the Schroeteri limestone, connects directly with the Platyurus limestone, and like the latter and the rest of the Orthoceras limestone of Västergötland, it is relatively free of interstratified shales. Towards the upper part of the Chasmops series the clay content increases; the limestone becomes more marly, and shales appear in packs of several metres' thickness.

The pyroclastic layers, changed by weathering to metabentonite, are a valuable guide in comparing the Middle Ordovician series of strata of different areas. Silification of calcareous and argillaceous sediments in a part of the section is particularly marked in Västergötland, and it has its special lithogenetic interest.

To judge from the drillings on Kinnekulle (at Kullatorp and Norra Skagen), the Middle Ordovician there has a thickness of approx. 40 m, with distribution over the various zones as shown by JAANUSSON and STRACHAN (1954, p. 691). A more detailed description of the series of strata at Kullatorp has been given by THORSLUND (1948, p. 343). On the lithology THORSLUND (1948, p. 350) writes: "The most striking feature of the Kullatorp core sequence compared with that of known Chasmops Series in Central and Northern Sweden is the great content of argillaceous material. Pure limestone beds are almost absent, and the limestone is mainly concentrated in two parts of the core, a lowermost one — and an upper one — the latter part including a central portion of intervening beds of altered volcanic material, bentonite, together about 2,2 m thick. The sequence between these parts mainly consists of mudstone and shale, more or less calcareous, with very sparse intercalations of argillaceous limestone."

The details given by THORSLUND of the drill section at Kullatorp are of great value from a stratigraphic point of view, too. Here a few particulars will be reported concerning the occurrence and development of the limestones in the upper part of the series. Beneath the black Tretaspis shale (with *Climacograptus styloideus*) follow, according to THORSLUND (1948, p. 343):

Limestone, dark-grey, slightly argillaceous and glauconitic	0,12 m
Shale, black, bituminous (with *Dicranograptus clingani*)	0,97
Limestone, grey — dark-grey, partly conglomeratic	1,38
Limestone, three beds, each of them built up of a lower portion of grey, almost compact limestone, and an upper portion of darker, finely crystalline limestone with glauconite and small lumps of dark phosphatic limestone	0,32

Limestone, grey, almost compact, with dark shale	0,75
Bentonite, pale-green	0,50
Limestone, argillaceous, dark, hard, towards the base increasingly flinty (68 % SiO_2)	0,35
Bentonite with aragonite	1,70
Limestone, grey, finely crystalline, with dark-grey, marly shale. In the upper portion cherty beds	2,45
Bentonite beds with shale, mudstone, and limestone	3,84
Mudstone, dark-grey, calcareous, with limestone and bentonite	8,26
Oolitic calcareous mudstone with argillaceous limestone	0,30
Limestone, grey, argillaceous, with mudstone	—

The lower part of the Chasmops series was drilled at Norra Skagen. Beneath the oolitic layer there followed, according to THORSLUND (1948, p. 360):

Limestone, greyish with reddish portions, finely crystalline or almost compact, with intercalations of shaly matter	12,5 m
Shale and limestone	7,5

The series of strata given above are typical of Kinnekulle. In other parts of Västergötland a somewhat different development has been met with. The lack of natural exposures and the want of drillings and excavations mean that only scattered, highly incomplete details can be given about the limestones of these areas. The examples of Chasmops limestone from Västergötland given below are only intended to illustrate the varying, but characteristic development of the rock.

Schroeteri limestone in Västergötland.

"Leversten" — "Upper grey Orthoceras limestone".

The oldest part of the Middle Ordovician of Västergötland, the Schroeteri limestone, formerly reckoned as the uppermost part of the Orthoceras limestone, is grey, greyish-pink, brownish-grey, often marly but with occasional solid beds of 10 cm. The thickness of the Schroeteri limestone is approx. 20 m on Kinnekulle, somewhat greater on Billingen. Cephalopods occur throughout in several genera and species. Trilobites are less common; of them *Illaenus schroeteri* might be mentioned. At a certain niveau there are abundant cystoidean tests of the genus *Echinosphaerites*. On Kinnekulle some beds of the rock are called "leversten" ("liver stone") on account of their colour, denseness, and dull shine, which recall boiled liver.

Below, the Schroeteri limestone of Kinnekulle will be illustrated together with a divergent type from Billingen.

Schroeteri limestone, Kinnekulle.

Typical "leversten".

Macro: Flint-dense, dull, greyish-pink with greyish-green tinges. The rock is darker and more argillaceous than "rosig östersjökalk" ("pink Baltic Sea limestone"), but it resembles the latter in deneness, conchoidal fracture, and tendency to be pink. Bedding planes uneven and with greyish-green marl.

Micro: Microcrystalline, granular (calcite grains 1—5 μ). Pigment submicroscopic. Micrococquina, completely recrystallized, fairly abundantly; larger fragments of trilobites and cystoideans only occasionally (fig. 143).

Diagenesis: Slight crystallization of the calcareous mud.

Formation: Precipitation and deposition of fine calcareous mud in quiet, probably somewhat deeper water than during the sedimentation of the Platyurus limestone.

Schroeteri limestone, Öglunda, Billingen.

Macro: Typical "leversten". Dense, uniformly greyish-brown. Weathering-crust light yellowish-grey. No macrofossils.

Micro: Ground-mass crystalline with calcite grains 2—5 μ and recrystallized microcoquina (fig. 144). Scattered larger fragments, mostly less than 1 mm. Ostracods with thin smooth shells, less than 0,5 mm; a few small gastropods, fragments of crinoids, and (not many) very corroded cystoidean tests. The microcoquina and the fragments are more or less accumulated in different parts of the rock. The pigment is not very noticeable under the microscope.

Diagenesis: Recrystallization of the calcareous mud and fragments.

Formation: Deposition in quiet, but shallow water. Neutral environment.

Nodular limestone, Öglunda, Billingen.

In the upper part of the limestone series which outcrops in the rivulet east of Öglunda Church, a sample of rock was taken, which, to judge by its appearance, belongs to the lowermost part of the Chasmops series. Its stratigraphic position is not established, however, and in lithologic development, e. g. silification, it recalls younger strata.

Macro: Bed 6 cm thick, with relatively even but slightly pitted bedding planes. The matrix consists of dense, hard, streaky dark and light grey marlstone with nodules and knobby lenses of dense, olive-coloured (green-brown-grey) limestone. The lenses have a length parallel to the bedding planes of 2—20 mm (fig. 34, p. 53). A number of them are elongated and clearly affected by sliding of the sediment.

Micro: The nodules and lenses consist of cryptocrystalline calcite. The matrix consists of microcrystalline calcite (grains 3—5 μ) with argillaceous pigment. Fossil fragments occur as frequently and of the same type in the lenses as in the remainder of the rock. Small smooth-shelled ostracods, trilobite fragments, occasional gastro-

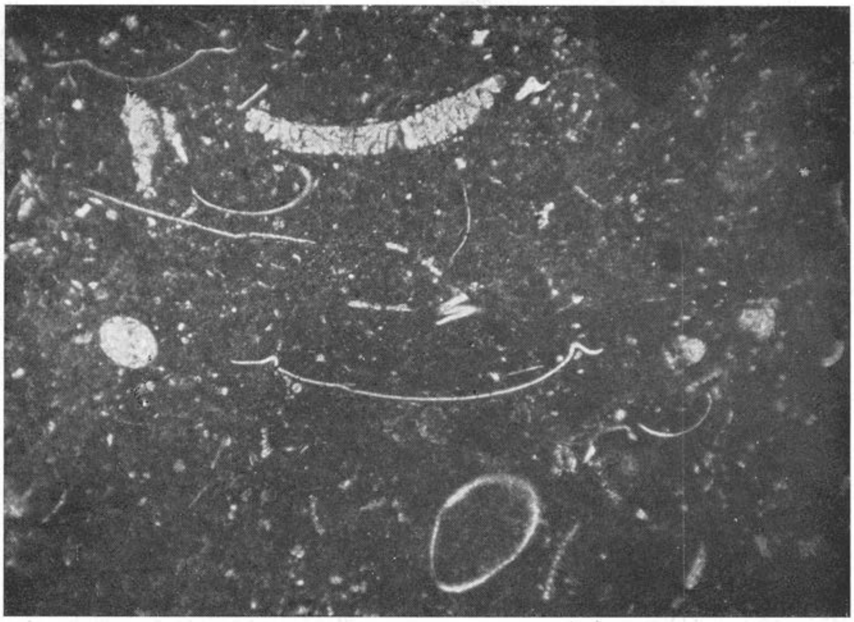


Fig. 143. Microcrystalline, flint-dense limestone. "Leversten". Schroeteri limestone, Middle Ordovician. Kinnekulle, Västergötland. (Prep. 3031, photo 1761.) — 20 ×.

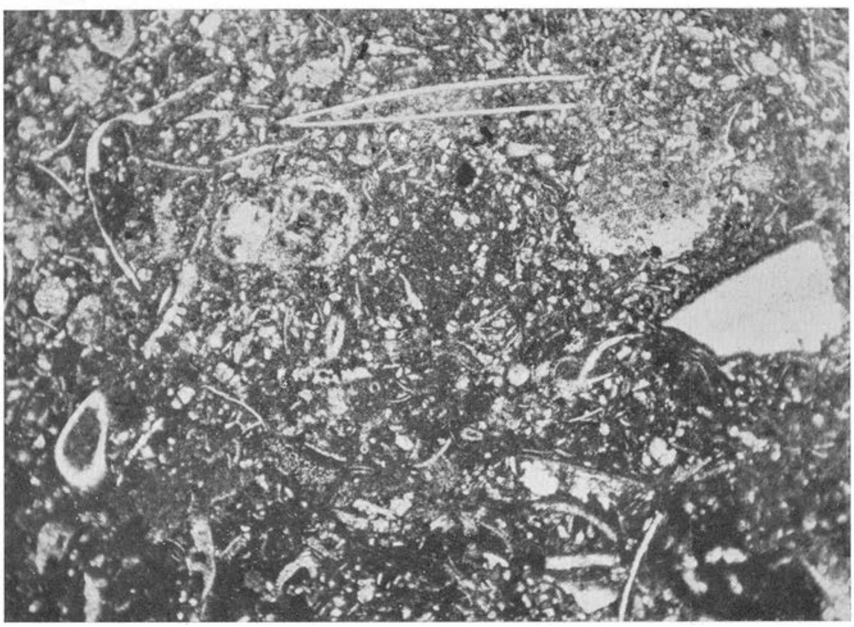


Fig. 144. Microcoquina limestone. "Leversten". Schroeteri limestone, Middle Ordovician. Öglunda, Västergötland. (Prep. 8776, photo 1612.) — 20 ×.

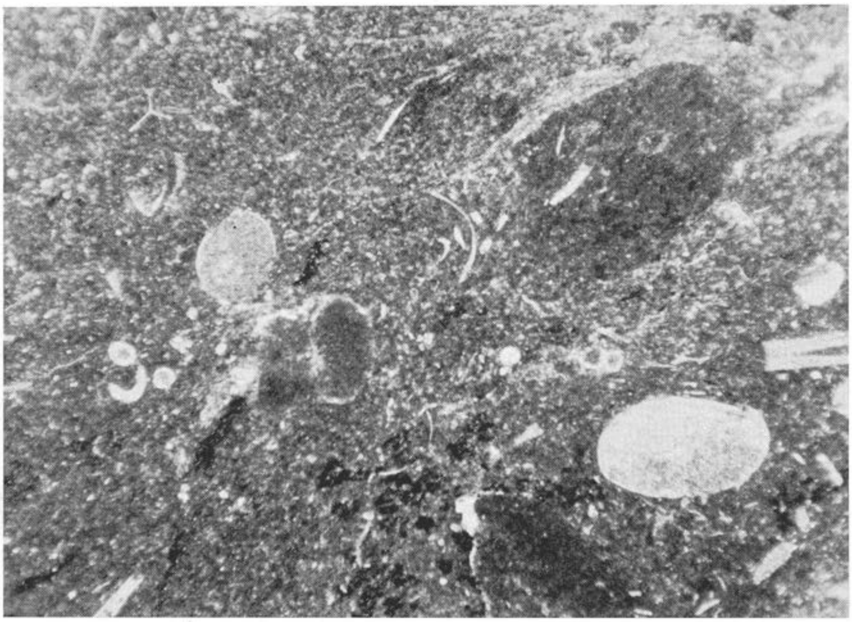


Fig. 145. Argillaceous, partly silicified limestone with cryptocrystalline, calcareous nodules. Chasmops limestone, Middle Ordovician. Öglunda, Västergötland. (Prep. 7254, photo 1709.) — 20×.

pods, and three-pointed sponge-spicules have been observed (fig. 145). Slickensides with fluidal structures around the lenses appear on strong enlargement and crossed nicols in the fine chalcedony needles which occur abundantly in certain parts of the mass.

Diagenesis: Crystallization of the calcareous mud and a slight silification, which is not found, however, in the portions consolidated earliest, the cryptocrystalline lenses.

Formation: The material has been deposited as calcareous mud in quiet, not altogether shallow water. During diagenesis an imperceptible sliding took place, in which the portions already consolidated came to be embedded as dense, knobby lenses in the "fluidal" mass, which later, during continued consolidation, was silicified along the streaks most easily admitting circulating water.[1]

Chasmops limestone, Ålleberg.

In 1893, in a small quarry at the north end of Ålleberg, Ivar Wallerius made a collection of Chasmops limestone, and in the following year he described the rock.

[1] The nodules and knobby lenses show the same texture and may be of the same character as the Masur limestone (see p. 231 and 244).

The deposit had earlier been observed by LINNARSSON (1869, p. 45) and was later mentioned by MUNTHE (1906, p. 42). In other, smaller exposures, WALLERIUS was able to follow the upper parts of the series of strata. A number of gaps remained, however. WALLERIUS distinguished the following divisions beneath the Tretaspis shale:

4. Limestone with crinoids and *Trinucleus* sp. (uppermost)

— — —

3b. Bluish-grey and red limestone
3a. Shale with *Beyrichia costata* LINRS.

— — —

2. Marly shale with *Asaphus glabratus* ANG., abundant fossils.
1c. Limestone with fragments of trilobites.
1b. Limestone with *Echinosphaera aurantium* GYLL.
1a. Limestone with *Orthoceras* sp.

The rock of the above series has been examined in strata 1b, 3a, and 3b, which are described below.

Echinosphaerites limestone, Ålleberg.

WALLERIUS' stratum 1b.

Macro: Dark-grey with faint tinge of green, dense with greenish-grey ooids. *Echinosphaerites aurantium* tests, orthoceratites, and scattered fragments of trilobites.

Micro: Ground-mass of cryptocrystalline calcite (grains 5 μ) and microcoquina with grey argillaceous matter. Trilobite and pelmatozoan fragments and occasional gastropod shells (fig. 146).

The ooids are built up concentrically of thin layers or fibres of chamosite. The colour is light brownish-green. In certain grains a faint pleocroism is noted, pale yellow — yellowish-green. The ooids often contain a core (gastropod shells, crinoidal fragments), and they may have a crust of calcite. Calcite may also have replaced a part of the chamosite. The latter occurs also as infilling in gastropod shells and echinoid pores.

Diagenesis: Slight but complete crystallization of the calcareous mud.

Formation: Mud deposited in shallow but quiet water with sporadic washing-in of fragments and ooids. Weakly reducing environment.

Limestone in marl with Steusloffia (Beyrichia) costata.

WALLERIUS' stratum 3a.

Macro: Light greyish-green, microcrystalline limestone interstratified in darker greenish-grey, dense marlstone. Abundant small shell fragments in the limestone, *Steusloffia costata* in the marl.

Micro: Matrix of crystalline calcite (grains approx. 3 μ) and argillaceous matter.

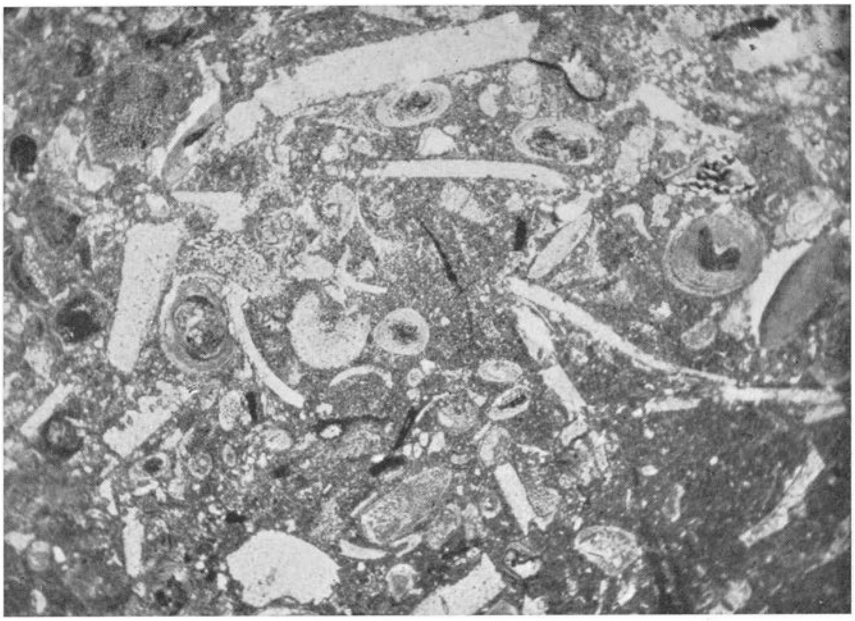


Fig. 146. Oolitic fragment limestone with microcoquina. Matrix of argillaceous, microcrystalline calcite. Echinosphaerites limestone, Middle Ordovician. Ålleberg, Västergötland. (Prep. 8792, photo 1614.)

Microcoquina (<0,05 mm) and larger fragments, including phosphatic shells, (mostly<1 mm) are found in abundance; there are also scattered ostracod shells and bits of pelmatozoans. Pyrite crystals and grains (< 10 μ) are scattered throughout the limestone. Quartz in angular grains (<0,2 mm). — Prep. 7094.

Diagenesis: Distinct recrystallization of the matrix, somewhat coarser calcite aggregates in and around shells. At the boundary between limestone and marlstone calcite aggregates in patches.

Formation: Calcareous, argillaceous mud together with small fragments deposited in quiet water at small depth (less than 200 m). Reducing environment.

Red Chasmops limestone, Ålleberg.

Wallerius' stratum 3b.

Macro: Brownish-red, dense limestone with scattered shell fragments and whole, smooth shells of ostracods.

Micro: Ground-mass of microcrystalline calcite (grains 5 μ) with hematite pigment and microcoquina (10—50 μ). Irregularly distributed fragments (0,3—3 mm) of trilobites, ostracods, crinoids (not many), and gastropods (scattered). In the earthy, red part (insoluble in hydrochloric acid) are found occasional grains of quartz (0,1 mm) and brown flakes of mica (0,1—0,3 mm). — Prep. 8793.

Diagenesis: Slight crystallization of calcareous mud.

Formation: Deposition of mud and fragments in quiet, shallow water. Oxidizing environment.

Chasmops limestone, Skogastorp.

In limestone at Skogastorp on the north side of Plantaberget, LINNARSSON (1869) found *Chasmops conicophthalma* SARS and BOECK, and later WALLERIUS (1894) pointed out *Asaphus glabratus* and *Lonchodomas* (*Ampyx*) *rostratus* in a highly fossiliferous limestone in the same place. The limestone is covered by a loose, greyish-green marly shale (with *Steusloffia costata*), which, according to WALLERIUS, is directly overlain by Tretaspis shale. The limestone, which (according to WALLERIUS) is locally conglomeratic in the upper part, has the following character:

Macro: Limestone bed, in lower part light-grey, microcrystalline, in upper part dark-grey, dense, with numerous phosphatic nodules, 0,2—2 cm in diameter. Weathering-crust grey and yellowish-grey.

Micro: The lower part of the bed consists of calcite grains, 5—10 μ, and abundant microcoquina and fragments less than 0,5 mm. The shells are completely recrystallized and mainly surrounded by radiated calcite. There is no phosphorite in this part of the bed.

The upper part has a calcite matrix with grains 1—5 μ. Largish fragments occur more numerously than in the lower part. Phosphatic shells, bits of pelmatozoans, and small quartz grains, both round and angular, occur scattered throughout the sediment. The phosphatic nodules are rounded (fig. 147a), but the numerous flocks of phosphorite, which form an essential part of the mass, are irregularly lobate. A few very much rounded balls of limestone have been observed. They are of the same type as the limestone in the lower part of the bed, but they are partly phosphatized. — Pyrite occurs partly in the form of small crystals scattered throughout the bed, partly as concretions in the upper part of the bed. There pyrite also occurs as a crust on and inclusion in phosphorite.

Between the lower non-phosphatic microcoquina limestone and the upper phosphatic limestone there is a clearly marked corrosion-surface (fig. 147b).

Diagenesis: Recrystallization particularly noticeable in the lower, lighter part.

Formation: After deposition of microcoquina, argillaceous and calcareous mud in quiet water, corrosion has taken place. In at times turbulent water coarse fragments have been transported to the sedimentation-site and mixed with mud. The phosphorite has been formed partly during the period of corrosion (nodules), partly immediately afterwards. Reducing environment.

Chasmops limestone, Mossen, Kinnekulle.

At Mossen east of Högkullen the following section was opened up in 1945 by MALTE ANDERSSON:

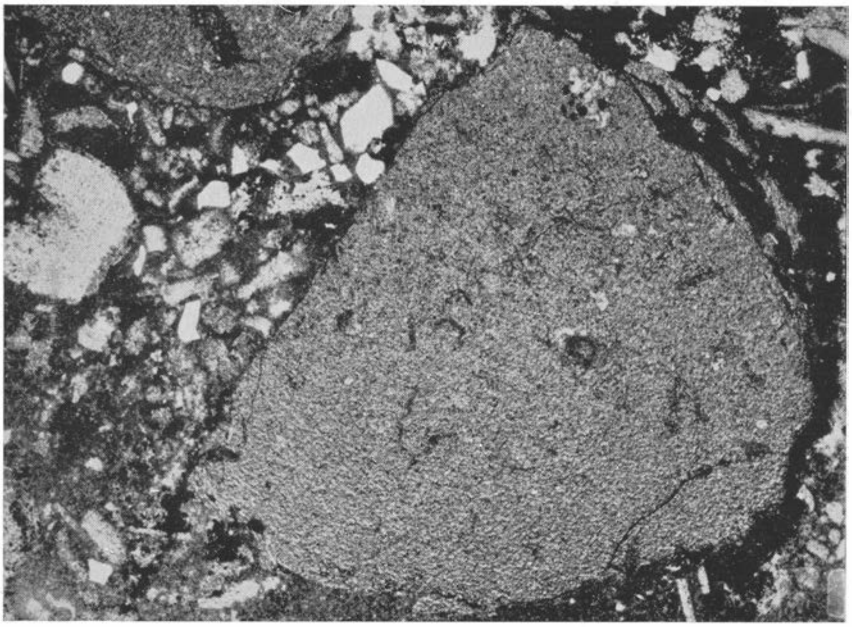


Fig. 147 a. Phosphatic nodule in fragment limestone. Chasmops limestone, Middle Ordovician. Skogastorp, Västergötland. (Prep. 7096, photo 1356.) — 20×.

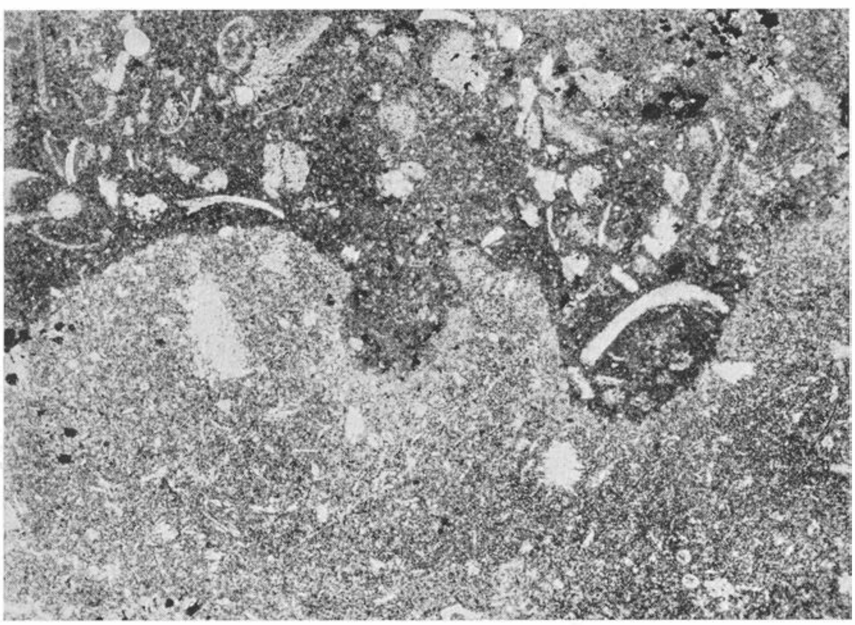


Fig. 147 b. Microcrystalline microcoquina limestone with corrosion surface. Chasmops limestone, Middle Ordovician. Skogastorp, Västergötland. (Prep. 7096, photo 1355.) — 20×.

K_3	Limestone in beds of 0,2—0,3 m with shale in layers of 0,05—0,1 m	3,0 m
B_2	Bentonite with interstratified, silicified limestone bed	0,6 m
K_2	Limestone, hard, silicified	0,4 m
B_1	Bentonite	1,7 m
K_1	Limestone	—

The series of strata corresponds to the upper limestone-bentonite strata of the drilling at Kullatorp (see p. 190). The limestones are of other types than those described earlier, and so a short report will be given on them.

K_1 *The limestone lowermost in the section at Mossen.*

Macro: Light greyish-green, dense, hard limestone with darker patches. Shell fragments sparsely scattered about the sediment. Loose, greyish-green marlstone adheres to the bedding planes of the limestone.

Micro: Matrix of granular calcite (grains approx. 2 μ) and argillaceous matter, microcoquina (mostly 10—200 μ), and small diffuse grains of quartz (7—40 μ). Larger fragments occur sparingly (fig. 148). Glauconite in a few dark-green grains (10—50 μ). Pyrite is almost completely missing; only a few very small crystals have been observed.

Diagenesis: Distinct but slight crystallization of calcite.

Formation: Argillaceous and calcareous mud deposited in quiet, not deep water. Shelf sediment. Neutral environment.

K_2 *Limestone in the middle of the section at Mossen.*

Macro: Silicified limestone. Dark-grey and dark greenish-grey, dense, hard, with conchoidal fracture and flint-sharp fracture edges. Weathering-crust reddish-brown.

Micro: Matrix of argillaceous matter and extremely fine-grained calcite (crystals 1—3 μ and less), to a considerable extent replaced by silica, partly as hazily bordered portions of quartz, partly as isotropic opal. Chalcedony in radiated aggregates has only been observed in the opal. Shell fragments, thin, decayed, and covered or replaced by a dark substance (iron sulphide), occur in small quantities. Glauconite in isolated small grains, 25 μ in diameter. — Prep. 8033.

Diagenesis: Slight crystallization of calcareous mud. Extensive silification, in which the calcite has been displaced by silica leached from the surrounding pyroclastic sediments.

Formation: (primary) Argillaceous and calcareous mud deposited in calm water in the shelf-belt. Neutral environment.

K_3 *The limestone uppermost in the section at Mossen.*

Macro: Olive-grey with faint tinge of brown and red. Dense, dull, argillaceous. A few shell fragments.

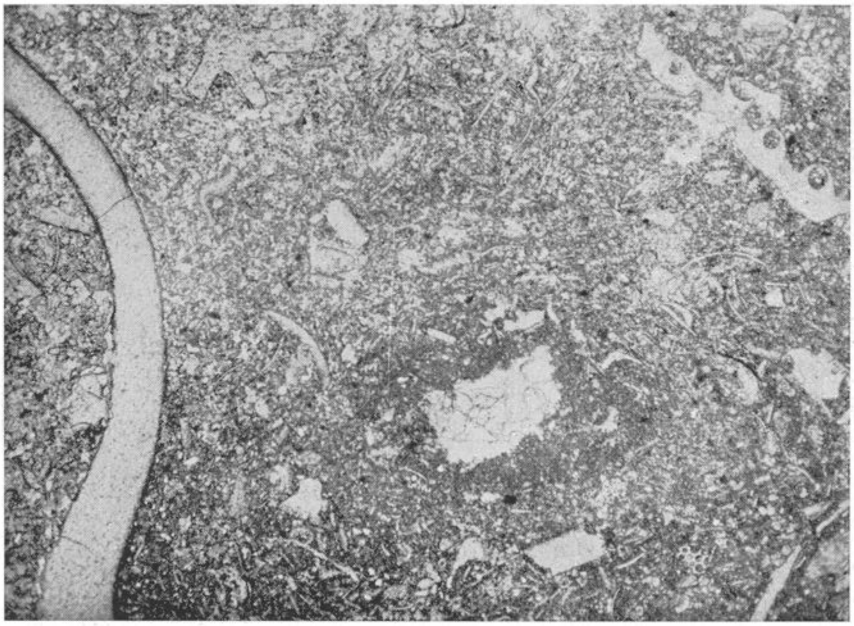


Fig. 148. Argillaceous microcoquina limestone. Chasmops limestone, Middle Ordovician. Mossen, Kinnekulle, Västergötland. (Prep. 8800, photo 1597.) — 20×.

Micro: Microcrystalline, even-grained calcite (grains 5—10 μ). Submicroscopic argillaceous pigment. Fairly abundant small shell fragments, extremely thin (3—6 μ); larger fragments rare. The fossils are completely recrystallized. — Scattered or here and there accumulated small crystals of pyrite surrounded by brown limonite-impregnated zone. — Prep. 8038.

Diagenesis: Recrystallization of calcareous mud and fossils.

Formation: Argillaceous and calcareous mud deposited in quiet water in the shelf-belt. Weakly reducing environment.

Chasmops limestone, Kinnekulle.

Blocks in large quantity. J. C. Moberg coll. 1892.

Macro: Dark-grey, flint-dense, splintery, slightly brecciated with white veins of calcite; Bituminous, faint smell of petroleum when struck. No macrofossils observed.

Micro: Matrix of calcite with grains 1—2 μ (fig. 149). Pigment only distinguishable as a muddy and faint brown colour in the calcite aggregate. Microfossils occur partly in the form of slightly flattened balls (diameter approx. 40 μ), partly in the form of small fragments, ostracods (0,1—0,5 mm) and crinoids. A few grains of quartz (<50 μ). No pyrite. — Lithologically this dense, bituminous Chasmops limestone is of the same type as the dense, bituminous limestone at Tand in the Lockne field (see p. 205).

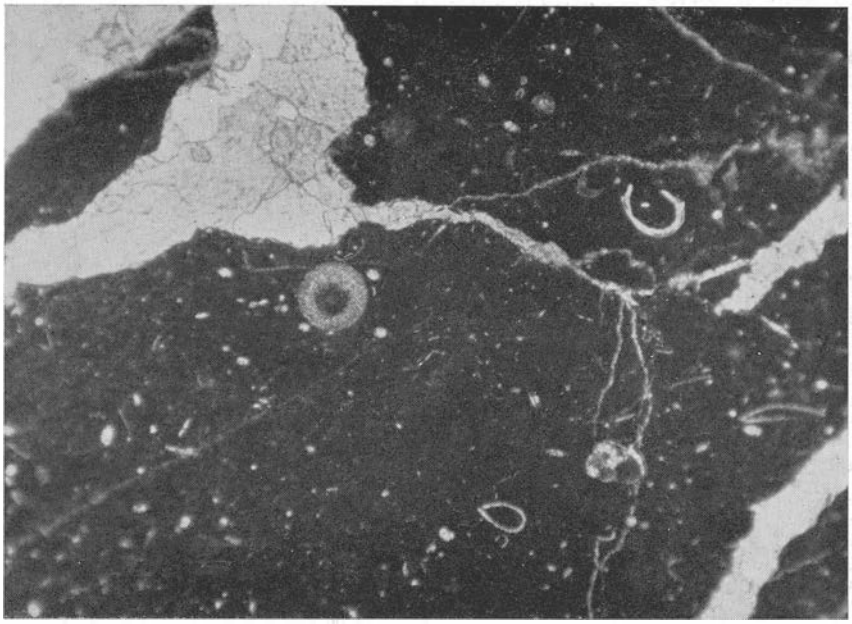


Fig. 149. Microcrystalline, flint-dense limestone with calcite veins. Chasmops limestone, Middle Ordovician. Kinnekulle, Västergötland. (Prep. 7093, photo 1763.) — 20×.

Diagenesis: Despite the bitumen-content only slight crystallization of the calcium carbonate (cf. anthraconites). Brecciation-cracking and formation of the calcite veins are of the same type as in septaria balls (shrinkage and crystallization phenomena).

Formation: Calcareous mud containing abundant organic matter sedimented in quiet water, relatively closed but without deposition of iron sulphide. Reducing environment.

The Middle Ordovician limestones of Östergötland.

The Middle Ordovician of Östergötland is only imperfectly known. Exposures are rare and small. LINNARSSON (1882, p. 24) distinguished two divisions in the Chasmops limestone: a lower with *Beyrichia* (*Steusloffia*) *costata* and *Caryocystites* (*Heliocrinites*) *granatum* WAHL and other cystoids, and an upper division with *Chasmops macrourus* SJÖGR. and *Ampyx* (*Lonchodomas*) *rostratus* SARS. The rocks are grey limestone and green marly shale. JÖNSSON (1887, p. 19) mentioned several localities with marl and limestone belonging to the Chasmops series. The rock at North Fredberga, which belongs to the lower part of the series, was reported to be rich in cystoids, *Caryocystites* (*Heliocrinites*) *granatum*, *Echinosphaerites aurantium*, etc. As the rock here has a somewhat special character, a description of it will follow.

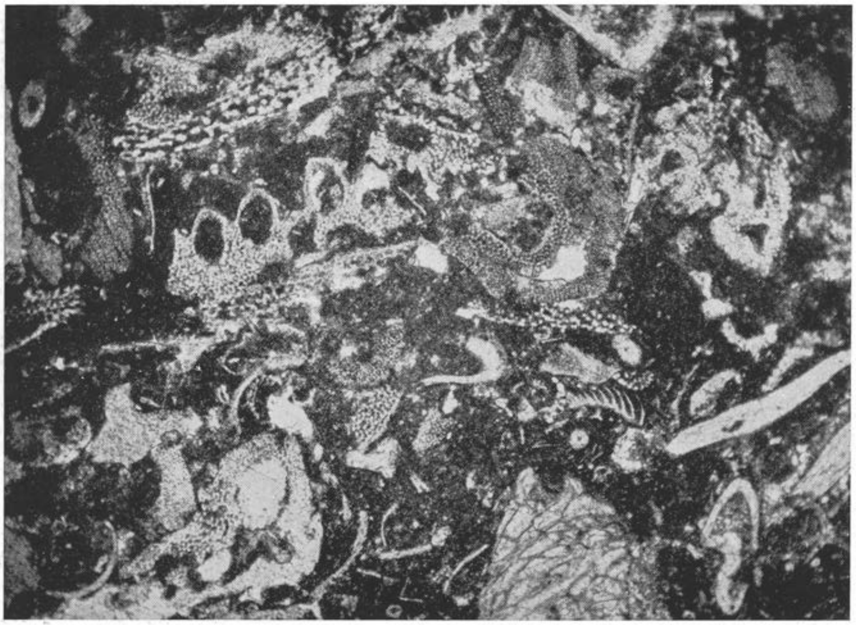


Fig. 150. Fragment limestone with pelmatozoans. Matrix argillaceous, microcrystalline calcite. Chasmops limestone, Middle Ordovician. N. Fredberga, Östergötland. (Prep. 7781, photo 1629.) — 20 ×.

Chasmops limestone, N. Fredberga.

Macro: Light-grey, crystalline, coarse or medium-coarse, with white or greyish-brown weathering-crust. Beds 2—5 cm.

Micro: The greater part of the matrix is crystalline, rather coarse-grained, but here and there we find dense, strongly argillaceous portions. In the latter calcite crystals of diameter 3—5 μ. The rock is chiefly composed of fragments of pelmatozoans and trilobites (fig. 150). In the coarse-grained beds the fragments measure mostly 1—3 mm; in the fine-grained 0,5—2 mm. Small ostracods (0,3 mm) and microfossils in the form of round, calcite-filled balls, 0,1 mm in diameter, occur mingled with microcoquina in the matrix.

Diagenesis: Extensive recrystallization in the larger part of the sediment.

Formation: Sedimentation in at times turbulent water with transportation even of coarser fossil fragments. The deposition of argillaceous and calcareous mud together with the fragments indicates that there cannot have been any constant flow or turbulent movement. Neutral environment.

The Middle Ordovician limestones of Jämtland.

The Middle Ordovician series of strata in Jämtland is very varying. In certain areas it has developed as graptolitic shales, in others as limestones and marly shales.

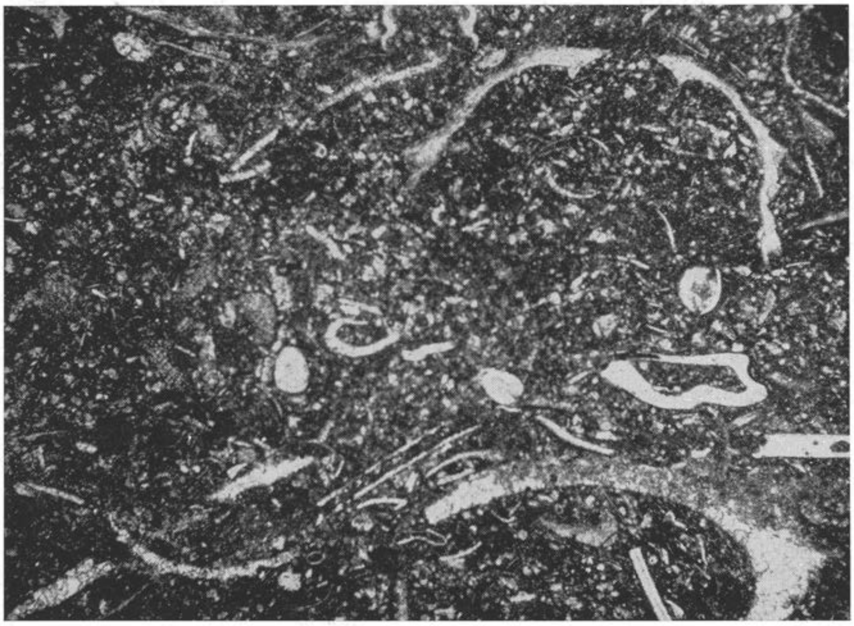


Fig. 151. Micrococquina limestone. Schroeteri limestone, Middle Ordovician. Skute, Lockne, Jämtland. (Prep. 7246, photo 1622.) — 20 ×.

Disturbances during sedimentation, breaks and conglomerates, in certain cases peculiar sediments, lend a special interest to the sequences of strata. A comprehensive investigation has been published by THORSLUND (1940), and valuable data have previously been given by WIMAN (1894 and 1900), besides which certain special conditions have been discussed by HADDING (1912, 1913, and 1927). Many problems concerning the Ordovician series of strata of Jämtland are still unsolved, and they are worthy of being taken up for thorough examination in a single context. Only in that way can we get a clear picture of the conditions of formation of the Middle Ordovician limestones and the sediments following them. A few forms of limestones are illustrated below.

Schroeteri limestone, south-east of Skute st:n, Lockne field.

Directly beneath "Loftarstone" conglomerate.

Macro: Dense, dark-grey limestone.

Micro: Microcoquina limestone. Ground mass microcrystalline (grains approx. 5 μ) with microcoquina (particles mostly less than 20 μ). Pigment grey or greyish-brown, somewhat bituminous. Small ostracods common, gastropods rare. Fragments of brachiopods, trilobites, and, less frequently, pelmatozoans (fig. 151). Irregular argillaceous bands. No grains of quartz or other rock fragments. — Pyrite in small cubes, accumulated in patches.

Diagenesis: Slight crystallization of the calcareous mud.

Formation: Calcareous mud with microcoquina and coarser fossil fragments deposited in quiet, not altogether shallow water. No weathered or brecciated Archean-rock shore can have been in the immediate neighbourhood of the sedimentation area. The limestone bed must have been (partly) consolidated before it was covered by the coarse "Loftarstone" conglomerate with its high content of fragments of granite and sedimentary rocks, including Schroeteri limestone.

Chasmops limestone, Tand, Lockne field. A.

East of Öhntjärn there is a relatively continuous section of limestones belonging to the upper part of the Asaphus series and the lower part of the Chasmops series (see THORSLUND 1940, fig. 15). Three types of limestone will be mentioned from this site:

A 1. Argillaceous microcoquina limestone
A 2. Fragment limestone
A 3. Flint-dense limestone, bituminous
A 4. Knobbily bedded limestone ("Backstein limestone")

A 1. *Microcoquina limestone, Tand.*

Macro: Dense, brownish-grey limestone, divided by meandering, dark, argillaceous streaks into balls and lumps of varying size and shape. The structure is a result of tectonic movements, which have also and more strongly been vented in folding and forming pseudo-conglomerates. — No macrofossils have been observed in the limestone, but its stratigraphical position shows that it must belong either to the upper part of the Asaphus series or to the lower part of the Chasmops series.

Micro: Crystalline, fine-grained calcite (1—10 μ), richly mixed with argillaceous matter, partly reddish-brown. Microcoquina (<0,1 mm) occur in large quantity; larger fossil fragments only sparingly. A few conical gastropods (1,4 mm), pelmatozoan fragments, and smooth-shelled ostracods (0,3—0,5 mm). Pyrite has not been observed; neither have grains of quartz or other coarse inorganic fragments. — Prep. 7248.

Diagenesis: Crystallization of the calcareous mud and fragments complete but without formation of coarse aggregate.

Formation: Argillaceous and calcareous mud deposited in quiet water, not at great depth but either not in the immediate vicinity of the shore, from which coarse products of weathering could be brought to the site of deposition. Probably oxidizing environment.

A 2. *Fragment limestone, Tand.*

Macro: Fine-grained, grey with dense, dark portions.

Micro: Distinctly worn, rounded fragments (0,5—1 mm) in a microcrystalline, argillaceous and bituminous calcite matrix (fig. 152). Fragments of pelmatozoans, trilobites, brachiopods, bryozoans, and ostracods. Inorganic coarse-detritus in the form of quartz grains etc. has not been observed.

Diagenesis: Slight recrystallization of the matrix.

Formation: The relatively large, partly much worn fragments must have got their rounded form in an environment other than that in which they are now located. Embedding in the mud has occurred secondarily in quiet water with only occasional stirring-up or during turbulent flow. Some stratification with alternate mud layers of high and low fragment-content is found in the rock.

A 3. *Dense, bituminous limestone, Tand.*

Macro: Unstratified, flint-dense, black, bituminous limestone, splintery and somewhat brecciated with white calcite veins and black, shiny slickensides. The rock appears as a lens, two metres thick, in thin-bedded limestone and shale.

Micro: Micro- and cryptocrystalline calcite (grains 1—3 μ) with black (brown in transmitted light), amorphous, bituminous substance (fig. 153). Of fossils only small calcite-filled, spherical or ellipsoidal shells, 0,1—0,2 mm. There is no pyrite, no grains of quartz or other coarse weathering-products.

Diagenesis: Slight but distinct crystallization.

Formation: Uncertain. Continued study of the limestone and its variations should enable us to determine the mode and the environment of formation. THORSLUND considers that the limestone closely resembles the Masur limestone of Dalarna (THORSLUND 1940, p. 50).

A 4. *Knobbily bedded limestone, Tand.*

Macro: Dense, dark-grey limestone with hard, irregular knobs or lenses in softer, more argillaceous and shaly mass. On weathering of the limestone the calcite is leached leaving a porous, dark-brown, soft but solid rock with a "Backstein" texture.

Micro: Argillaceous, slightly bituminous, microcrystalline limestone (grains 1—15 μ), with abundant micrococquina ($<$0,2 mm) and a few smooth-shelled ostracods (0,2 mm) and calcite-filled balls (40 μ). Hazily bordered quartz, occasionally in distinguishable grains (10—25 μ), occurs in varying quantity, most abundant where the "Backstein" texture is best preserved (e. g. prep. 7146 and 7249, rock specimen 6327). No large shell fragments have been observed, nor any coarse weathering-matter. Small brown patches of bitumen occur scattered throughout the sediment. No pyrite.

Diagenesis: Slight but complete crystallization of the calcareous mud; slight and irregular silification, which had a binding effect when the calcite was dissolved on weathering.

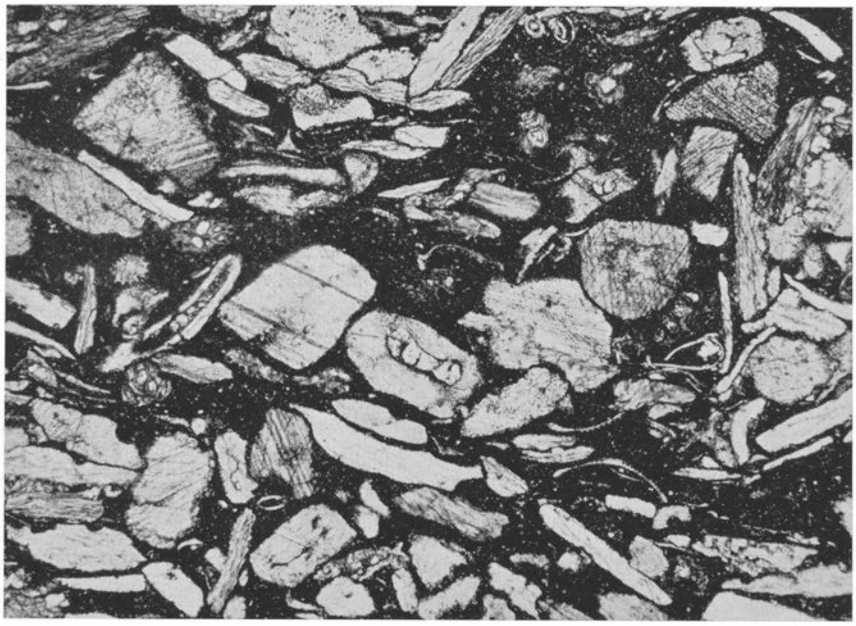


Fig. 152. Argillaceous and bituminous fragment limestone with redeposited material. Chasmops limestone, Middle Ordovician. Tand, Jämtland. (Prep. 694, photo 1367.) — 20×.

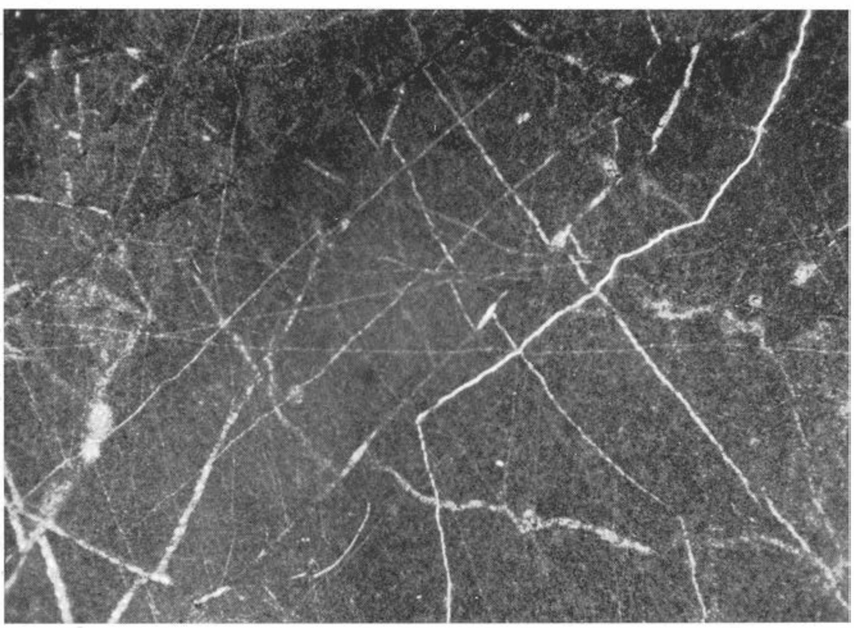


Fig. 153. Micro- and cryptocrystalline limestone. Chasmops limestone. Tand, Jämtland. (Prep. 7250, photo 1659.) — 20×.

Formation: Deposition of argillaceous and calcareous mud together with organic matter in quiet water without supply of coarser organic or inorganic material. Reducing environment.

Chasmops limestone, Tand, Lockne field. B.

Somewhat different from that in the section described above is the appearance of the Chasmops limestone 2 kilometres east of Öhntjärn, halfway between Tandsbyn railway station and Lappgrubban. The limestone there reposes directly upon Archean granite. The brecciated basal conglomerate grades rapidly over into pebble-less, dense limestone, which in turn is overlain by bedded limestone and shale. According to THORSLUND (1940, p. 46) the whole of this series of strata belongs to the Chasmops stage. A few types of rock will be mentioned:

B 1. Dense, argillaceous limestone with granite shivers
B 2. Fragment limestone with pelmatozoans
B 3. Dense Bryozoan limestone with *Echinosphaerites*

B 1. *Dense, argillaceous limestone with granite shivers. Tand.*

Macro: Dark-grey, dense mud-limestone with scattered fossil fragments. In the mud a varying content of sharp-edged granite shivers and lumps of limestone.

Micro: The ground-mass, the calcareous mudstone, consists of microcrystalline calcite (grains 10 μ) with a rich mixture of argillaceous matter, microcoquina, scattered larger fragments, and some bitumen (fig. 154 and fig. 155). The limestone lumps embedded in the mud all have a relatively low content of argillaceous matter, but otherwise they are of varying nature and have different contents of fossil fragments. They are slightly rounded. The granite shivers are not weathered and generally have thin, sharp edges; they are never worn or rounded.

Diagenesis: Slight crystallization of the calcareous mud.

Formation: The sediment was primarily deposited in quiet, not shallow water so far from the shore that only the finest inorganic (argillaceous) detritus was deposited together with calcareous mud and fossil fragments. Both the limestone balls and the calcareous matrix of the rock testify to the conditions of formation. Rearrangement of the material has occurred, however. This rearrangement took place without separation or wear of the material. The unconsolidated mud with fossil fragments and consolidated limestone lumps came into contact during sliding with brecciated granite, with the result that a number of fragments of the granite were included in the mud mass.[1] The peculiar composition and texture of the limestone have been

[1] THORSLUND (1940) considers that the limestone with granite fragments discussed above is a normal shore formation, arisen during a transgression and comparable with the coquina limestone of north-east Skåne's Cretaceous deposits. The latter were formed during transgression

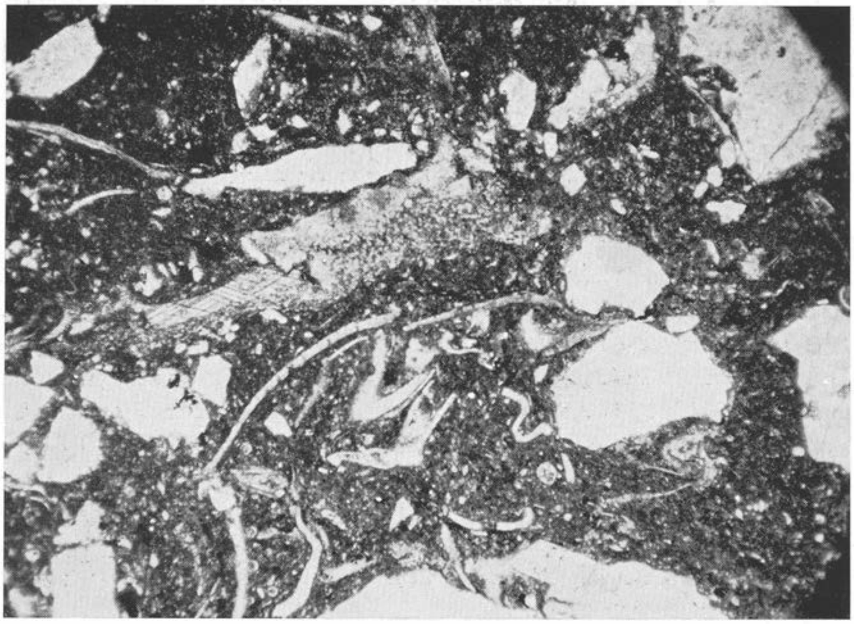


Fig. 154. Argillaceous microcoquina limestone, conglomeratic, with lumps of microcoquina limestone and granite shivers. Chasmops limestone (Loftarstone conglomerate), Middle Ordovician. Tandsbyn, Jämtland. (Prep. 5981, photo 1694.) — 20 ×.

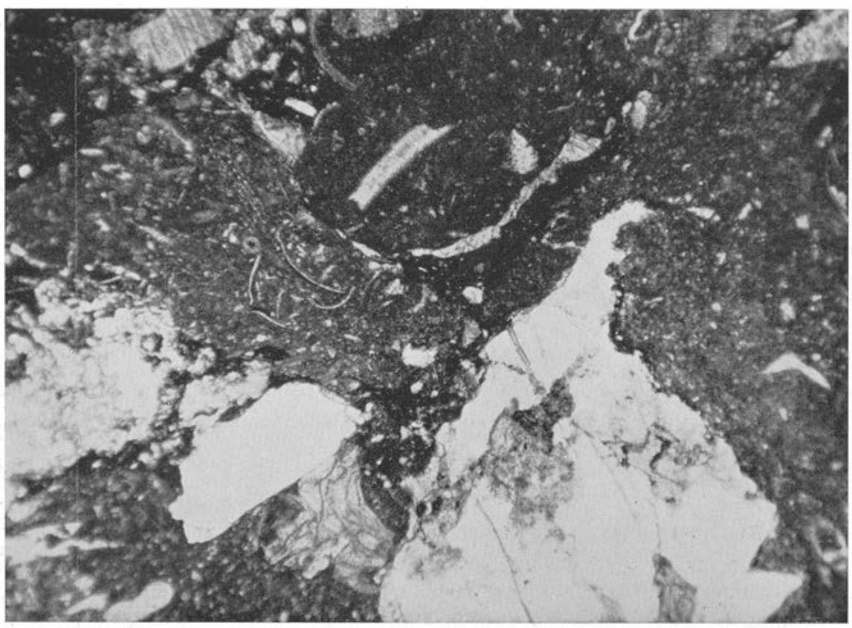


Fig. 155. Microcoquina limestone with redeposited material. Conglomeratic. Lumps of limestone (dark), shivers of granite (white). Chasmops limestone (Loftarstone conglomerate), Middle Ordovician. Tand, Jämtland. (Prep. 5987, photo 1759.) — 20 ×.

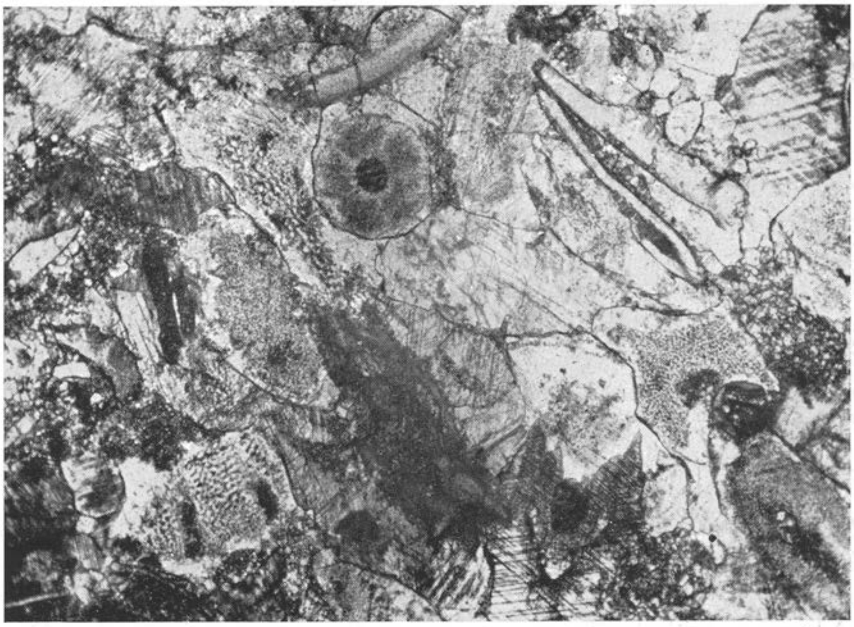


Fig. 156. Fragment limestone with pelmatozoans. Chasmops limestone, Middle Ordovician. Tandsbyn, Jämtland. (Prep. 2350, photo 1657.) — 20 ×.

ascribed to tectonic disturbances during the time of its formation (HADDING 1927 and 1929).

B 2. *Fragment limestone with pelmatozoans. Tand.*

Bed immediately above granite.

Macro: Heterogeneous limestone, partly fine-grained — dense, dark-grey, partly rather coarse-crystalline, light-grey. Of macrofossils fragments of trilobites, orthoceratites, and pelmatozoans, etc.

Micro: The fine-grained portions consist of calcite (grains approx. 20 μ) and argillaceous matter. In certain parts they contain scattered pelmatozoans; in other more argillaceous and dark parts, only microcoquina. — The coarse-crystalline portions consist of relatively pure calcite (grains 0,2—2 mm), abundant pelmatozoans, and coarse, worn trilobite fragments (fig. 156). The limestone consists of a mixture

over an area which since Silurian time had lain above sea level, and the Archean pebbles which are found in these limestones are worn and very much rounded. The Chasmops limestone discussed above was formed in an area which contains normal sublittoral sediments from the Upper Cambrian and Lower Ordovician (up to and including the Gigas-Platyurus and Schroeteri zones), thus an area which was transgressed long before and immediately prior to the Chasmops limestone being formed. If the latter had arisen during continued land-subsidence, the earlier deposited sediments would not have been broken up by erosion to become part of a shore sediment as mud or lumps.

of dissimilar sediment-masses, which have been moved to their present site in unconsolidated form. A remarkable fact is that the sediment does not contain (in the part dealt with here) any fragments of the underlying granite, or any coarse products of weathering. A distinct bitumen-content has been observed, however, and in certain portions it is so high that it can be traced even in the fibrous texture.

Diagenesis: Distinct crystallization of the calcium carbonate, with the smallest calcite crystals in the argillaceous portions.

Formation: The limestone consists of secondarily mixed calcareous sediments of primarily somewhat varying development and formation. The dark, very argillaceous microcoquina portions primarily formed part of mud layers deposited in quiet water without supply of coarse fragments; the pure portions of pelmatozoan and trilobite fragments, on the other hand, formed part of sedimentary layers deposited in more turbulent water and at less depth. During transition between the formation of these two sedimentary types the calcareous, not very argillaceous mud with scattered pelmatozoan fragments was deposited. None of these three elements was primarily formed as a shore deposit: they all belong to the sublittoral, shallow-sea zone, like the next oldest and youngest parts of the series of strata. How the sediments came to be mixed and situated on the granite is a question that will not be discussed here.

B 3. *Bryozoan limestone with Echinosphaerites. Tand.*

Macro: Dense, light-grey limestone with white calcite aggregates, large, dark fragments of trilobites, and tests of *Echinosphaerites*.

Micro: Matrix microcrystalline calcite (grains 10—30 μ) with argillaceous matter and microcoquina. Scattered larger fragments, even of bryozoans (fig. 157). Pelmatozoans occur only sparingly; they are completely recrystallized, diffuse. Pyrite crystals and small pyrite aggregates lie scattered throughout the bed. No quartz grains, granite fragments, or other coarse inorganic matter.

Diagenesis: Slight crystallization.

Formation: Argillaceous and calcareous mud deposited in quiet water without supply of coarse weathering-material.

The Middle Ordovician limestones of Öland.

The Cambro-Silurian of the island of Öland, which from the Middle Cambrian reaches up into the Chasmops series, is largely occupied by the Orthoceras limestone. The slight dip of the layers towards the east means that we only find the Cambrian strata on the west coast of the island and the Middle Ordovician only on the east coast. Outcropping Chasmops strata younger than the Schroeteri limestone are not much exposed, and only in the northernmost part of the island do they form the bedrock.

Fig. 157. Fragment limestone with bryozoans. Matrix argillaceous microcoquina and microcrystalline calcite. Middle Ordovician. Tand, Jämtland. (Prep. 7145, photo 1695.) — 20 ×.

The limestones of Öland's Middle Ordovician which are discussed below are:

Macrourus limestone	=	only known as erratic blocks.
Ludibundus limestone	=	comprising also Echinosphaerites limestone
Crassicauda limestone	=	formerly called "Lower Chasmops limestone"
Schroeteri limestone	=	formerly designated "Upper grey Orthoceras limestone" (also Chiron, Centaurus, or Ancistroceras limestone. See p. 116, note 2).

The terms Crassicauda and Ludibundus limestone launched by JAANUSSON (1947 and 1951) have been adopted here to indicate that the limestone occurs in the lower or the upper part respectively of the series of strata between the Schroeteri and the Macrourus limestone.

Schroeteri limestone, Öland.

The oldest part of the Chasmops series, the Schroeteri limestone, consists of microcrystalline, grey beds, often hard and relatively thick. The latter applies especially to the uppermost part of the series, the Ancistroceras limestone. Apart from the index fossil, *Illaenus schroeteri*, the zone contains several species of trilobites (*Megalaspis patagiata*, *Ogygiocaris dilatata*, *Telephus bicuspis*, etc.). The youngest

Fig. 158. Fragment limestone with microcoquina and microcrystalline calcite grains. Schroeteri limestone, Middle Ordovician. Brunnby, Öland. (Prep. 3261, photo 1349.) — 20×.

beds are rich in *Ancistroceras undulatum*. In marly, loose strata between the limestone beds whole, rolled-up specimens of *Nileus armadillo* have been found.

As transitional stratum to the actual Chasmops limestone is mentioned a bed overcrowded with cystoids (*Echinosphaerites*), which in a few places directly overlies normally developed Schroeteri limestone.

Schroeteri limestone, Brunnby.

Macro: Bed 4 cm. Bedding planes uneven, rough. Microcrystalline — dense, light-grey with faint tinge of yellow.

Micro: The major part of the limestone consists of microcoquina with grains 20—40 μ, embedded in a calcite matrix with grains about 4 μ. Argillaceous dust occurs uniformly intermingled with the calcite grains. There are a few pelmatozoan fragments, somewhat more other fragments (0,1—1 mm) and small shells. No glauconite or pyrite has been observed (prep. 7562).

Another bed from the same place has been found to consist of somewhat larger fragments, for the most part 0,2—2 mm large (fig. 158). Some of the fossils are impregnated with limonite.

Diagenesis: Crystallization of the calcareous mud.

Formation: Microcoquina and a small amount of argillaceous material deposited in quiet water, probably at greater depth than the Platyurus limestone. Non-oxidizing environment.

Schroeteri limestone, Källaberg.

The distance between Källaberg and Brunnby is 75 km, but there is no noticeable difference in the development of the Schroeteri limestone in the two places.

Macro: Microcrystalline, pure grey, with a few carapaces of trilobites (*Illaenus schroeteri*).

Micro: Microcoquina limestone with varying but small quantity of argillaceous matter in fine-grained calcite matrix. Microcoquina mostly 0,05—0,5 mm. — Prep. 6927.

Formation: As above.

Crassicauda limestone, Stensåsa.

Macro: Beds 2 cm. Dark-grey, microcrystalline, hard limestone with yellowish-white weathering-crust coated with small fossil fragments. The limestone contains irregularly scattered, black, smooth grains, which recall ooids, and a few larger grains or small balls with the same black coating. Winding, cylindrical worm-tracks, 2 and 4 mm in diameter, are visible on the bedding plane.

Micro: Microcrystalline calcite (grains approx. 5 μ) with some argillaceous matter, abundant microcoquina, and a small quantity of larger fragments of trilobites and pelmatozoans, also small gastropods and ostracods. The macroscopically visible black grains proved to be fossil fragments with a coating of a brown (in transmitted light) substance (limonite), which also fills shells or pores (fig. 159).

Diagenesis: Only slight crystallization.

Formation: Slightly argillaceous calcareous mud with microcoquina deposited in quiet water without supply of coarse weathering-matter. Fossil fragments from different environments mixed in. The relatively few fragments with coating or infilling of dark matter acquired it in an environment in which the remaining fragments were never present.

Ludibundus limestone, Böda harbour.

Macro: Beds uneven, 2—3 cm thick. Light-grey limestone with rough bedding planes coated with fossil fragments. Fragments of trilobites (e. g. *Chasmops conocophthalma*), bryozoans, brachiopods, and pelmatozoans.

Micro: Fragment limestone with trilobites, ostracods, brachiopods, gastropods, pelmatozoans, and bryozoans. The fragments occupy practically the whole of the rock (fig. 160). The matrix, which is partly extremely fine-crystalline (grains $<5\ \mu$), partly relatively coarse-crystalline calcite, can easily be completely overlooked. In some fragments a fine-grained, black pigment (iron sulphide) can be seen.

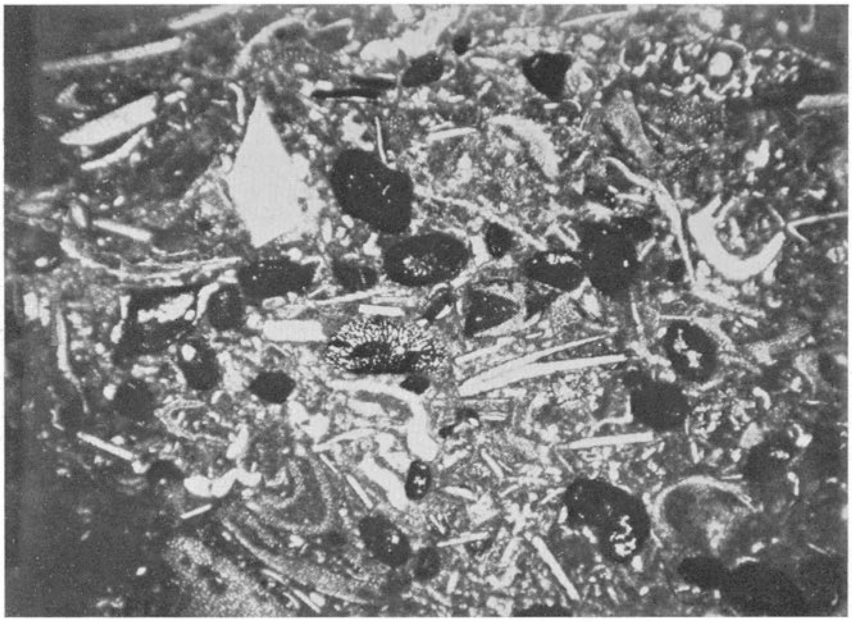


Fig. 159. Microcoquina limestone with limonite in porous fragments. Crassicauda limestone, Middle Ordovician. Stensåsa, Öland. (Prep. 6888, photo 1644.) — 20 ×.

Fig. 160. Fragment limestone with matrix of calcite. Ludibundus limestone, Middle Ordovician. Böda harbour, Öland. (Prep. 6619, photo 1350.) — 20 ×.

Diagenesis: In certain portions pronounced, but otherwise slight crystallization of the matrix.

Formation: Fossil fragments, for the most part less than one millimetre, deposited together with a few larger fragments and some mud in turbulent water.

Macrourus limestone, Ösby brook.

Macro: Greyish-white, dense, marly limestone with scattered macrofossils: trilobites (e. g. *Chasmops macrourus*), brachiopods, gastropods. The fossils in several cases have been dissolved, but the casts are well preserved. In the sediment cylindrical worm-tracks, 4 mm in diameter.

Micro: The matrix consists of microcrystalline calcite (grains approx. 10 μ), argillaceous mud, and small, angular grains of quartz (20—30 μ) (fig. 161). Microcoquina and larger fragments occur in rather small quantity (bryozoans, trilobites, pelmatozoans, and small gastropods).

Diagenesis: Slight crystallization.

Formation: Well-separated fine sand deposited together with microcoquina and (somewhat argillaceous) calcareous mud in shallow, slightly turbulent water.

Macrourus limestone, Hulterstad.

A quantity of very fossiliferous blocks of Macrourus limestone has been collected by S. L. Törnquist. The majority of the blocks are of the same type as those mentioned above from Ösby, and they contain cephala and pygidia of *Phacops macrourus*. Amongst the blocks, however, were some which were partially silicified and which contained lenses of flint. This rock has the following characteristics:

Macro: Dense, light-grey limestone, partly hard, silicified. A thin lens of bluish-grey flint is visible in the limestone. No macrofossils have been observed.

Micro: Matrix of microcrystalline calcite (grains 2—10 μ) with numerous, completely recrystallized fossil fragments: bryozoans, ostracods, pelmatozoans, brachiopods (fig. 162). The flint is murky in parts with calcareous mud; in the central parts it is crystallized as chalcedony.

Diagenesis: Crystallization of calcareous mud and fossil fragments. Silicification and formation of flint.

Formation: Calcareous mud with small fragments deposited in quiet water together with substance rich in SiO_2. In what form this substance primarily occurred in the mud is not evident from the present nature of the sediment. (The cause of silicification may be the same in Öland as in Västergötland: the presence of volcanic ash in the sediment. No layers of bentonite have yet been shown to exist in the Ölandian series of strata, however).

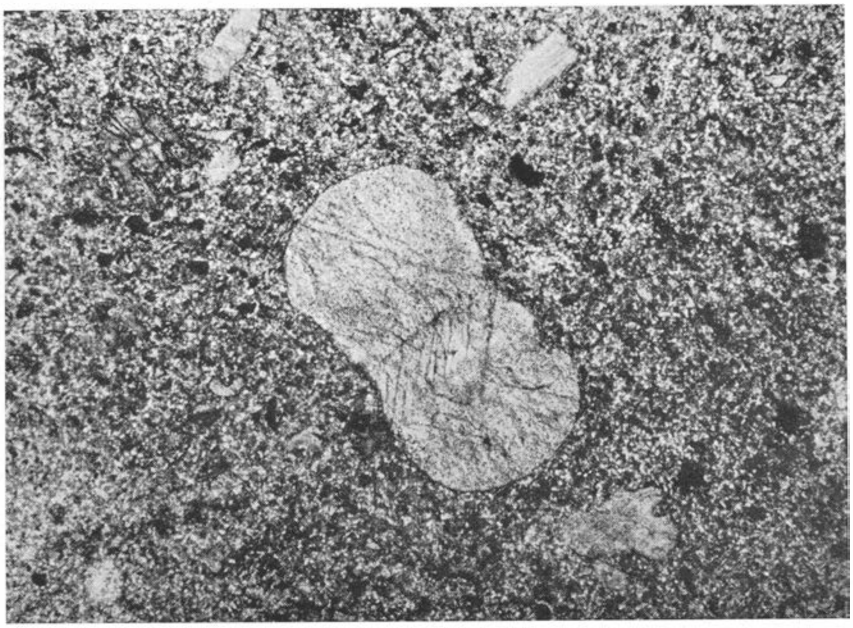


Fig. 161. Argillaceous, microcrystalline limestone (calcilutite) with pelmatozoan fragments. Macrourus limestone, Middle Ordovician. Ösby, Öland. (Prep. 3032, photo 1351.) — 20×.

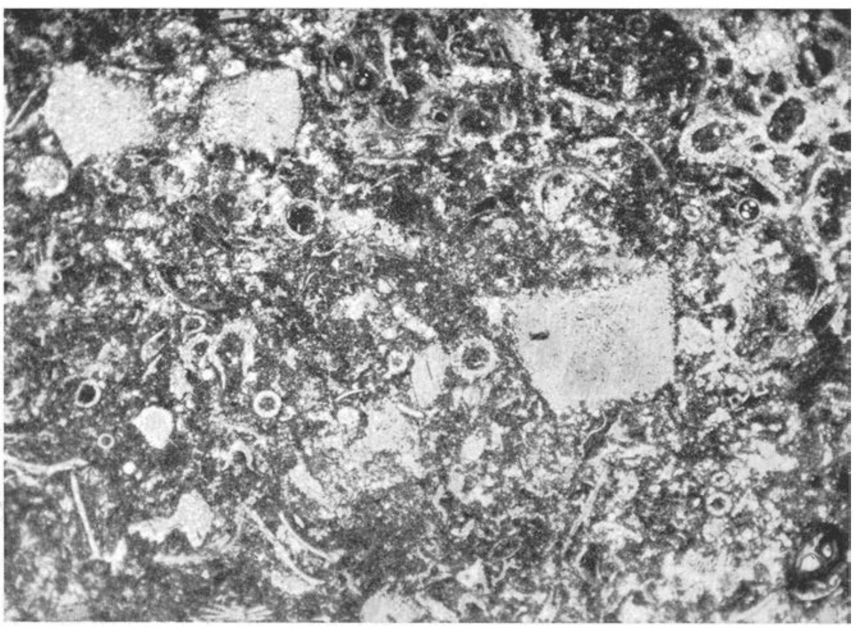


Fig. 162. Microcrystalline, partly silicified limestone with micrococquina. Macrourus limestone, Middle Ordovician. Hulterstad, Öland. (Prep. 7209, photo 1641.) — 20×.

The Middle Ordovician of Skåne.

The Middle Ordovician of Skåne is principally formed of black graptolitic shales (see scheme p. 184). In the middle and upper parts there are, however, insignificant beds of black, dense limestone: in the zone with *Climacograptus haddingi* there is a phosphoritic limestone with *Tretaspis bronni*, the Bronni limestone,[1] and above the zone with *Nemagraptus gracilis* lie scattered beds which correspond to the Ludibundus and Macrourus limestones. As the exact age of these beds is not known, this limestone is called simply Chasmops limestone in the following account.

Bronni limestone, Tommarp.

The Bronni limestone is well developed in south-east Skåne but is absent in the central and western parts of the county, as also on Bornholm, where it is replaced by shales. The series of strata in which the limestone occurs has been investigated by FUNKQUIST (1919). He reports the following section from Tommarp (1919, pp. 22—23):

Uppermost:	Shale with pyrite and phosphorite	30 cm
	Limestone, dense, dark-grey, with *Tr. bronni*	7 »
	Limestone, dark-grey, shaly, with *Tr. bronni*	9 »
	Limestone, dark, very pyritic, at bottom with phosphatic nodules and fragments	7 »
	Limestone, hard, rich in phosphorite and pyrite	5 »
	Phosphorite conglomerate with pyrite in black limestone	5 »
	Dark phosphoritic shale	10 »
	Limestone, shaly, with no fossils	3 »
	Orthoceras limestone, grey (Lower Asaphus and Limbata limestone)	

The very phosphoritic beds between the grey Orthoceras limestone and the Bronni limestone at Tommarp have their equivalents in western Skåne in a thick series of black graptolitic shales and in Öland in Upper Asaphus, Gigas and Platyurus limestone, and partly in Schroeteri limestone. Since the strata at Tommarp are less thick than elsewhere, one must either reckon with a big break in the series, as FUNKQUIST (1919) and POULSEN (1936) do, or interpret the phosphoritic strata as the result of slowly progressing, often interrupted sedimentation. The latter interpretation appears to be the most likely to the present writer, bearing in mind the conditions under which the phosphorite lumps were formed. The considerable deposition of iron sulphide speaks directly for sedimentation in a closed basin

[1] In older literature the limestone goes under the name of Coscinorrhinus limestone after *Tretaspis coscinorrhinus* ANG. (= *Tr. bronni* SARS and BOECK).

with only slightly turbulent water. The phosphoritic layers are an interesting local development of that part of the series of strata which in other places acquired normal shale or limestone facies. It should be further examined in connection with an investigation into phosphoritic rocks and their conditions of formation. Here only the actual limestone with *Trinucleus bronni* will be discussed.

Macro: Dense, greyish-black with brown, porous, argillaceous weathering-zone. Pyrite in small lumps nearest the bedding planes and as crystals scattered throughout the rock. Trilobites, e. g. *Trinucleus bronni*. Worm-tracks.

Micro: Microcrystalline, even-grained (calcite crystals approx. 5 μ), with dark-brown pigment (fig. 163). A few fossil fragments, mostly less than 1 mm. Occasional phosphatic shells, coprolites (0,6 mm), and small accumulations of phosphorite.

Formation: Mud-deposition in quiet water. Reducing environment.

In the lower, more pyritic, phosphoritic beds the limestone is dense, black, knotty. The pigmentation is irregular. Fossil fragments occur profusely. Infillings, crusts, and ooids of phosphorite (fig. 164).[1]

Chasmops limestone (1), Tommarp.

In the same series of strata as the Bronni limestone but on a niveau about 1,2 metres higher there is a thin bed (7 cm) of partly silicified limestone. The bed is characterized by FUNKQUIST (1919, p. 25, bed no. 34) as hard, calcareous shale with some pyrites and by NÖRREGAARD (1925, p. 18) as hard, dark shale with limestone, the latter microcrystalline and with argillaceous particles.

In the limestone bed in question the following division into bands can be distinguished:

---

[1] At Killeröd, about 9 km west-north-west of Tommarp, the Orthoceras limestone is exposed in a quarry. The overlying series of strata has been measured and examined by RAGNAR NILSSON. He reports (1951) the following section (in abridged form):

Uppermost:	Limestone and mudstone interbedded	70 cm
	Dark-grey shale and limestone	15 cm
	Shale, black at top, grey at bottom	119 cm
	Orthoceras limestone	

The upper strata with limestone and mudstone belong (according to NILSSON) to the zone with *Trinucleus bronni*, the dark-grey layers immediately beneath belong to the zone with *Climacograptus haddingi* ("putillus"). The 119-cm-thick series of shales immediately above the Orthoceras limestone belongs to the upper part of the Upper Didymograptus shale, the zone with *Pterograptus scanicus* ("Geminus shale"). The Orthoceras limestone belongs to the Limbata and Lower Asaphus zone.

The large break which exists, according to FUNKQUIST, between the Orthoceras limestone and the Bronni limestone at Tommarp is largely filled with shales at nearby Killeröd. A re-examination of the series of strata in south-eastern Skåne is to be desired. On Bornholm the Bronni limestone is absent. It has its equivalent in shales, partly phosphoritic (FUNKQUIST 1919, NÖRREGAARD 1925, POULSEN 1936).

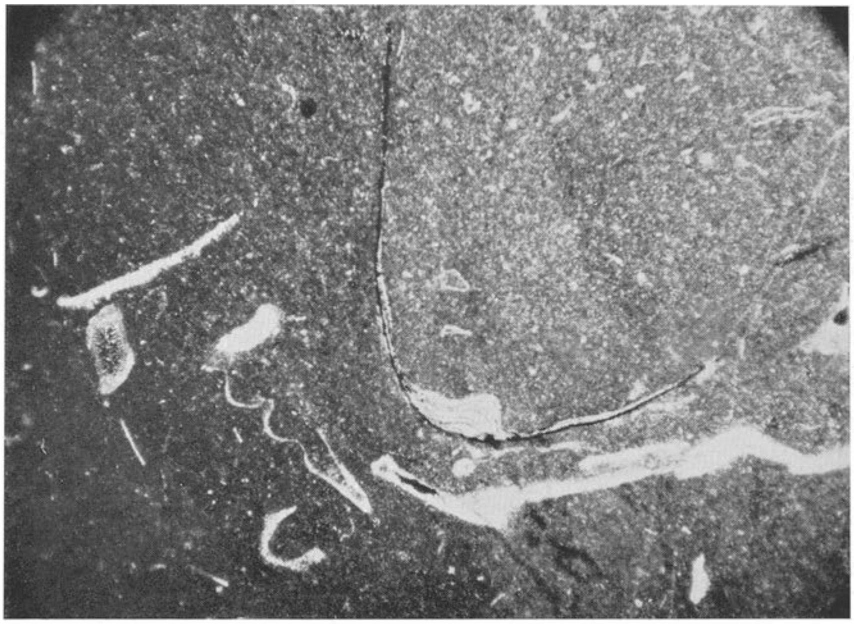


Fig. 163. Argillaceous, microcrystalline limestone (calcilutite). Bronni limestone, Middle Ordovician. Tommarp, Skåne. (Prep. 6539, photo 1699.) — 20×.

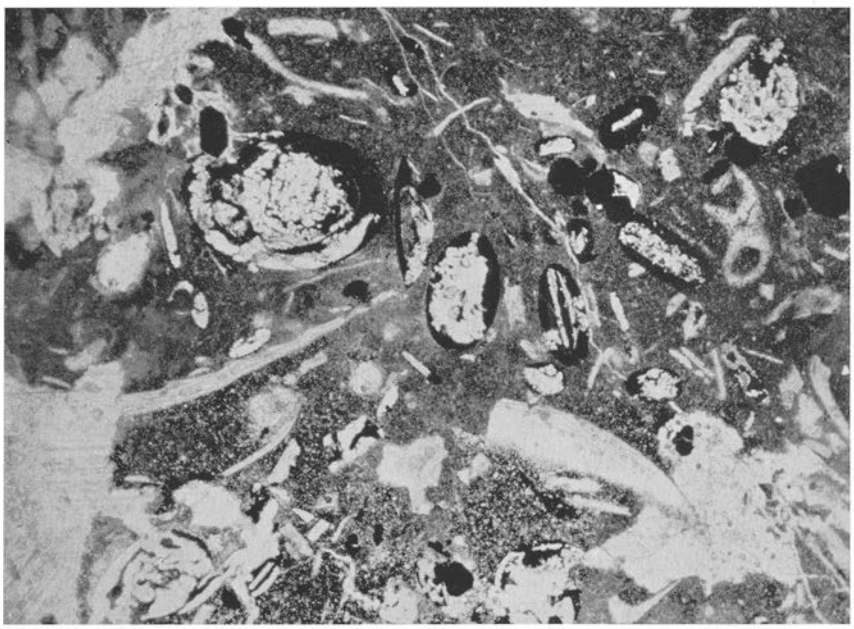


Fig. 164. Oolitic fragment limestone. Matrix of microcrystalline calcite with bitumen. Phosphorite (dark) and calcite partly replace the primary ooids. Bronni limestone, Middle Ordovician. Tommarp, Skåne. (Prep. 643, photo 1307.) — 20×.

(Uppermost)	Limestone, crystalline with free ends of sharp rhombohedrons at the bedding plane	0,5 cm
	Mudstone, somewhat calcareous. Silicified	1,0 »
	Mudstone, dark-grey with lighter worm-tracks. Silicified . .	3,0 »
	Limestone, microcrystalline, dark-grey (see below)	1,5 »
	Siliceous rock, black, flint-dense, with small remains of calcite	1,0 »

There is no marked boundary between the different bands. The part of the series of strata in which the limestone lies contains several layers of bentonite which have provided material for silicification of the limestone. As the latter is typical of the environment in which the series of strata has been formed, it has been included despite its small thickness.

Macro: Dark-grey, dense, slightly silicified, argillaceous limestone. After solution of the calcite in dilute HCl a brown, finely porous, backstein-like mass remains.

Micro: The matrix consists of irregular calcite crystals (0,1—0,4 mm) and a light-brown, (bituminous and argillaceous) cryptocrystalline siliceous mass (fig. 165, a—b). Pyrite occurs generally in small aggregates. A few fossil fragments, occasionally with a crust of fibrous calcite.

Diagenesis: Complete crystallization of the calcareous mud. On the other hand, there is only a slight trace of crystallization in the secondarily precipitated SiO_2 substance.

Formation: Deposition of mud in quiet water. Reducing environment.

Chasmops limestone (2), Tommarp.

Ampyx limestone

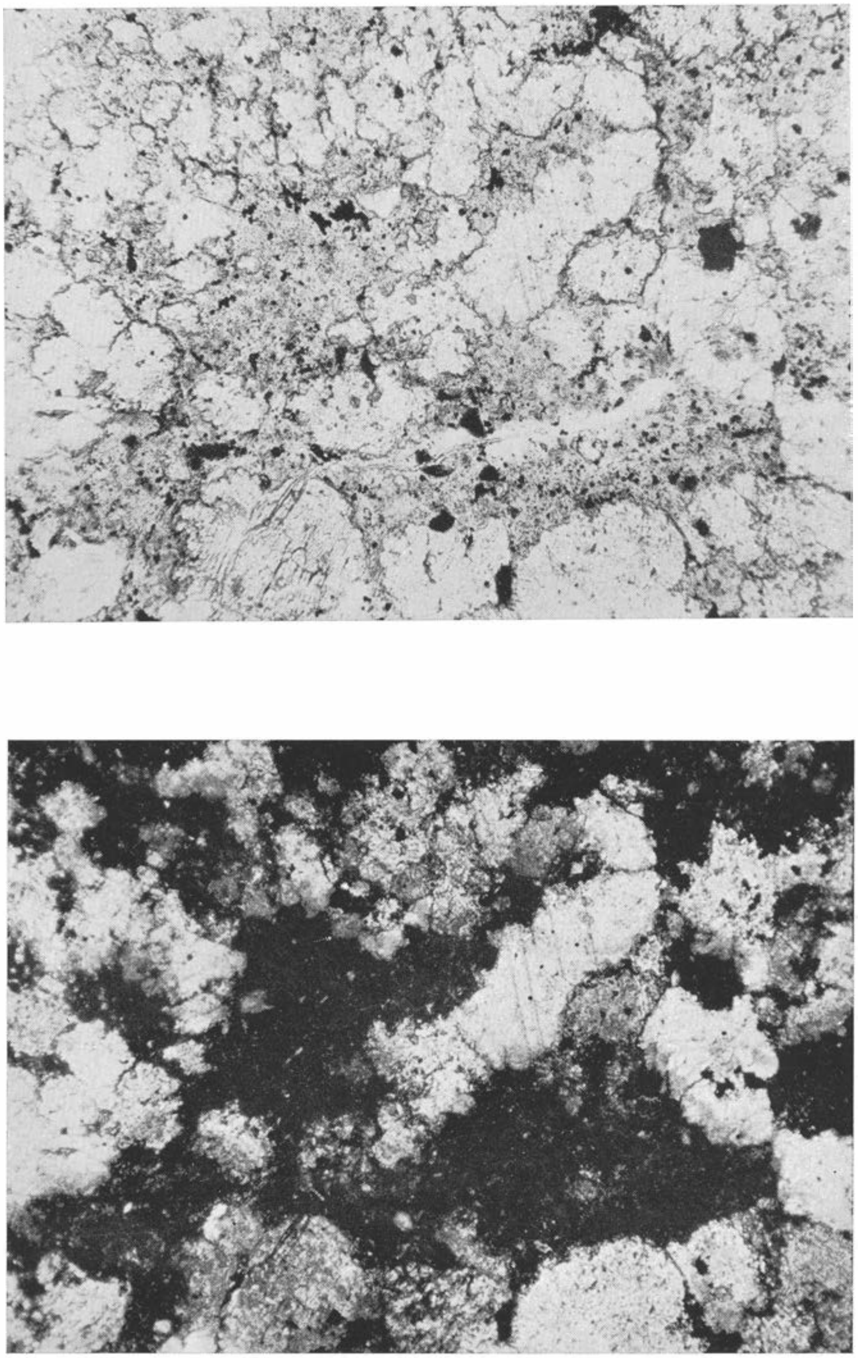
Beneath the zone with *Dicranograptus clingani* and about 3,4 metres above the Bronni limestone at Tommarp there are a number of limestone beds with *Lonchodomas (Ampyx) rostratus* Sars and *Asaphus glabratus* Ang., etc. Funkquist (1919, 25) and Nörregaard (1925, 19) call the limestone “Ampyx limestone”. The latter describes the rock as dark-grey, siliceous, and consisting essentially of microcrystalline calcite and fossil fragments but traversed by amorphous and cryptocrystalline silica. Quartz and biotite are found in small quantity. Pyrite and bitumen occur as pigment.

Macro: Black, crystalline limestone with trilobite and brachiopod fragments, pyrite, and scattered flakes of biotite.

Micro: Major part crystalline calcite (grains 0,05 mm) and numerous fossil fragments (0,2—1 mm) in dark-brown, argillaceous and bituminous matrix (fig. 166). Angular grains of quartz (approx. 0,1 mm) occur thinly scattered in the sediment. Pyrite in cubes and small aggregates.

Diagenesis: Crystallization of calcareous mud with displacement of bituminous, argillaceous substance.

a



b

Fig. 165. Silicified limestone. Chasmops limestone, Middle Ordovician. Tommarp, Skåne. (Prep. 6536, photo 1787 a-b.) — 20 ×. a. Nic. ||, b. Nic. +.

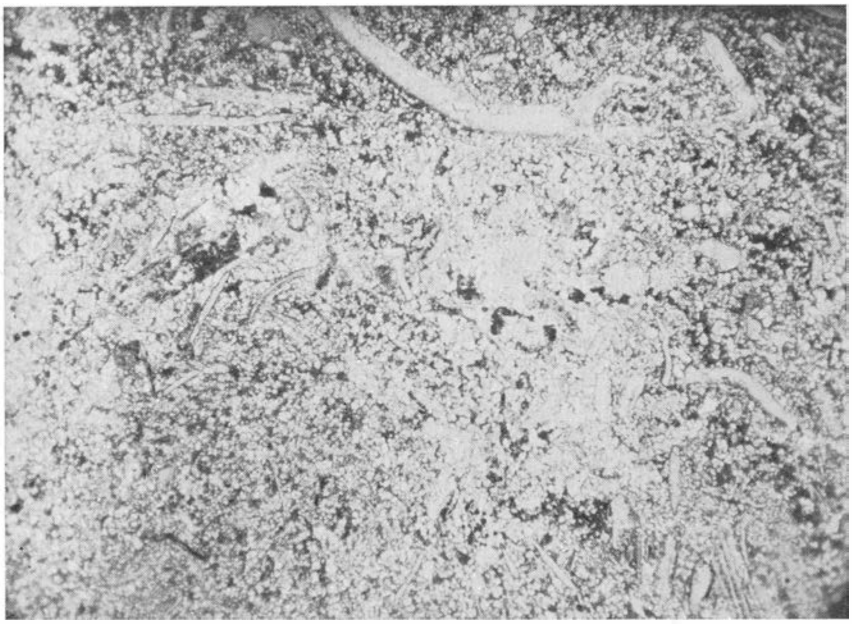


Fig. 166. Bituminous, microcrystalline limestone. Chasmops (Ampyx) limestone, Middle Ordovician. Tommarp, Skåne. (Prep. 2059, photo 1693.) — 20×.

Formation: Calcareous mud with abundant fossil fragments and a smaller quantity of quartz deposited in quiet water together with iron sulphide and organic matter. Reducing environment.

Upper Ordovician limestones.

During the Upper Ordovician an elevation of land occurs, which is clearly noticeable in the marine sediments of southern and central Sweden. The black, red, and grey shales which dominate the Tretaspis series have been formed in shallow water, and the relatively negligible limestones which lie in the shales have a pronounced shallow-water character. Especially remarkable is the profusion of calcareous algae in these limestones. The Dalmanitina series contains arenacous strata, conglomerates, and oolitic limestones, which give the series a distinct shallow-water character. This is further strengthened by local occurrence of calcareous algae, including reef-forming types.

The two stages of the Upper Ordovician, the Tretaspis and the Dalmanitina series, show a varying development in the different sedimentation areas. In Skåne they consist almost entirely of grey shales with scattered limestone beds, always highly argillaceous. In Västergötland there are several completely different types: dense limestone, oolitic limestone, coral limestone, etc. Similar forms, but others, too, occur in Dalarna and Östergötland. In Öland there are interesting forms with a different development, e. g. Paleoporella limestone.

The Upper Ordovician limestones of Skåne.

The Upper Ordovician, the Tretaspis and the Dalmanitina series, is principally in the form of shales in Skåne, usually grey or black. Calcareous strata occur, however, partly as marly shales, partly as argillaceous limestones. The latter only rarely form an unbroken sequence. Usually one finds the limestones as isolated, not very thick beds. The limestones are dense, with few fossils, and with a brown, porous, earthy weathering-zone. No phosphorite or glauconite has been observed in them. Pyrite occurs only sporadically. In certain beds, however, barytes occurs in freely developed crystals or aggregates (see HADDING 1938). As typical of the limestones belonging to the Tretaspis stage of Skåne only the barytic limestone of Järrestad will be described. From the Dalmanitina stage a limestone from Röstånga is mentioned.

Tretaspis limestone, Järrestad.

Macro: Grey or faintly greenish-grey, argillaceous limestone with dark-grey, algae-like markings. Dense, dull with conchoidal fracture. Weathering-zone dark-brown, loose, earthy. No fossils observed. In one of the beds profuse barytes crystals (HADDING 1938).

Micro: Matrix of microcrystalline, even-grained calcite, with abundant completely recrystallized, dust-fine shell debris (20—50 μ). Argillaceous matter with (a few) angular grains of quartz (20—30 μ), regularly distributed throughout the sediment (fig. 167). No pyrite. — The barytes crystals contain and may partly be completely replaced by secondarily formed calcite. The sediment surrounding the barytes crystals also contains a certain quantity of BaO. (See HADDING 1938. Analysis by SVEN PALMQVIST.)

Diagenesis: Complete crystallization of the calcareous mud. Formation of barytes crystals.

Formation: Deposition of mud in quiet water. Neutral environment.

Dalmanitina limestone, Röstånga.

The Dalmanitina series is principally composed of shale in Skåne, partly arenaceous. Deposition of mud has proceeded in shallow water (TROEDSSON 1918 and 1920). The limestones occurring in the series are thin and always very argillaceous, occasionally bituminous (Nyhamn). Fossils occur only sparingly, mainly trilobites (*Dalmanitina mucronata* BROGN.). At Röstånga the Dalmanitina series has been incompletely exposed in a few places. Here the limestone in loc. III, i (MOBERG 1910, p. 118) will be chosen as an example of the development of the rock.

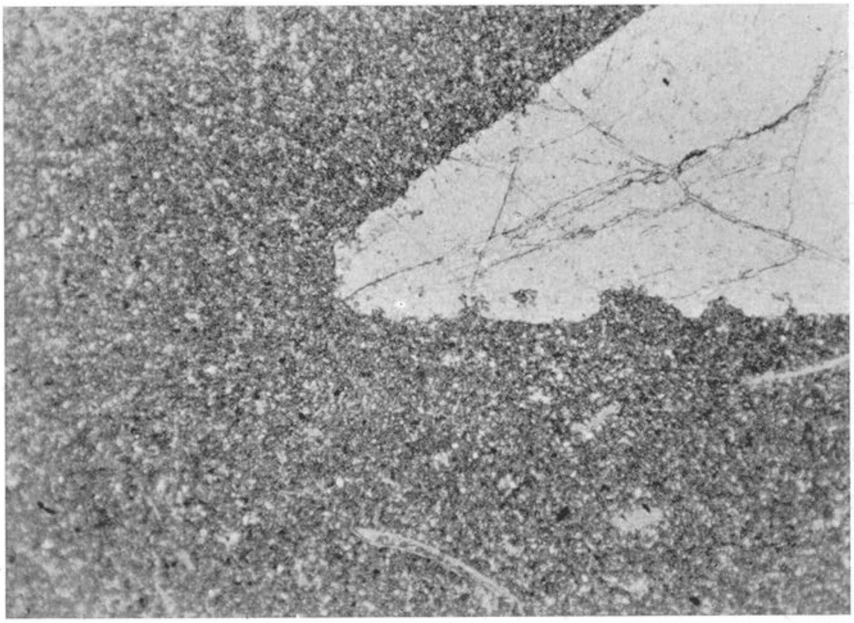


Fig. 167. Argillaceous, microcrystalline limestone with barytes crystal. Tretaspis limestone, Upper Ordovician. Jerrestad, Skåne. (Prep. 8904, photo 1719.) — 20×.

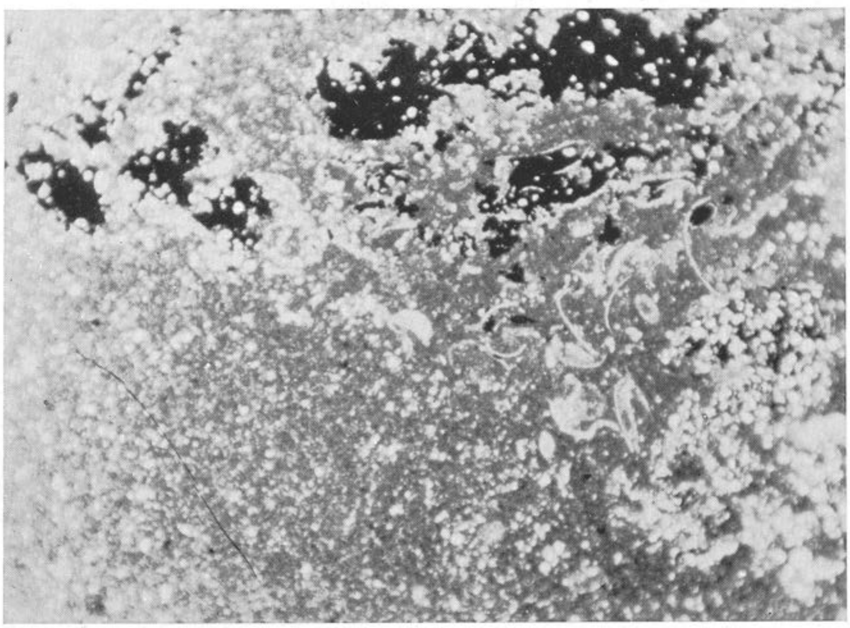


Fig. 168. Argillaceous, microcrystalline limestone with pyrite. Dalmanitina limestone, Upper Ordovician. Röstånga, Skåne. (Prep. 6884, photo 1718.) — 20×.

Macro: Dark-grey, dense, uniform in colour and density. No macrofossils have been observed. Deep weathering-zone, brown, earthy.

Micro: The limestone is largely microcrystalline (calcite grains 1—5 μ) and strongly pigmented. Here and there accumulated grains of quartz (20—100 μ) and small, thin shells of ostracods (fig. 168). Pyrite concretions.

Diagenesis: Not very noticeable recrystallization of the calcareous mud. The high content of argillaceous detritus has counteracted the formation of coarse-grained calcite. This condition is thus the direct opposite of that which can be observed in limestone with a high bitumen-content, e. g. anthraconite.

Formation: The normal sedimentation of argillaceous mud, small grains of quartz, and a small quantity of calcareous mud has been altered for a short time so that the relative quantity of calcareous mud has greatly increased. The cause of this may be either a reduction in the supply of argillaceous mud, e. g. as a result of isolation of the sedimentation area, or an increase in the production of calcium carbonate. One of the alternatives is supported by the occurrence of pyrite, the other by a somewhat increased content of calcareous fossils. A more deeply lying cause might well be changed conditions in the temperature of the water rather than a change in depth or turbulence of the water.

The Upper Ordovician limestones of Öland.

Upper Ordovician strata have not been observed outcropping in Öland, but blocks of limestone belonging to the Tretaspis series occur in several places, particularly on the east coast of the island. At Gräsgård canal there are several large slabs embedded in moraine, among them Upper Ordovician Paleoporella limestone, resting directly on Middle Ordovician Macrourus limestone. To the Tretaspis series belong also the blocks of (pink) Östersjö limestone and Masur limestone.[1]

Paleoporella limestone, Ösby.

Macro: White, "glistening", crystalline limestone with interlarded Paleoporella fragments.

Micro: The Paleoporella fragments occupy about half of the rock. They are completely recrystallized. The matrix consists of a diffuse algal mass with enclosed portions of microcrystalline calcite (grains 3—15 μ) and small fossil fragments (fig. 169). Pyrite occurs in a few small grains. No inorganic detritus has been observed.

[1] Also found as erratic blocks together with very fossiliferous Macrourus limestone (and, according to Törnquist (on labels), belonging to the latter limestone) is a partly silicified limestone with flint. As this rock, however, does not contain any determinable fossils, its age is uncertain. It is possible that it belongs to the Tretaspis series or to the oldest part of the Silurian. As it has not been possible to establish the age of the limestone, I have preferred to follow Törnquist's view, and it has therefore been mentioned with the Middle Ordovician limestones of Öland.

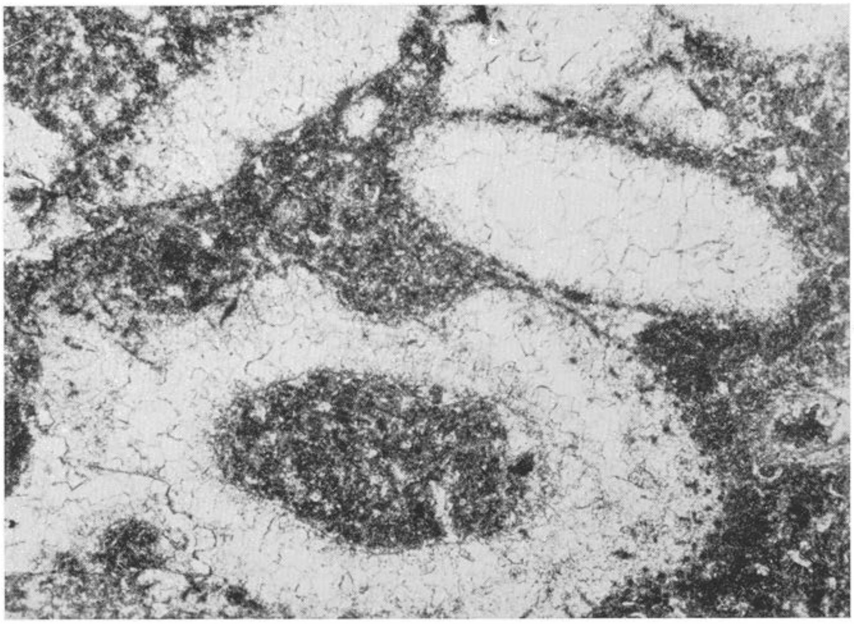


Fig. 169. Paleoporella limestone with partly cryptocrystalline, algal matrix. Upper Ordovician. Ösby, Öland. (Prep. 6621, photo 1352.) — 20 ×.

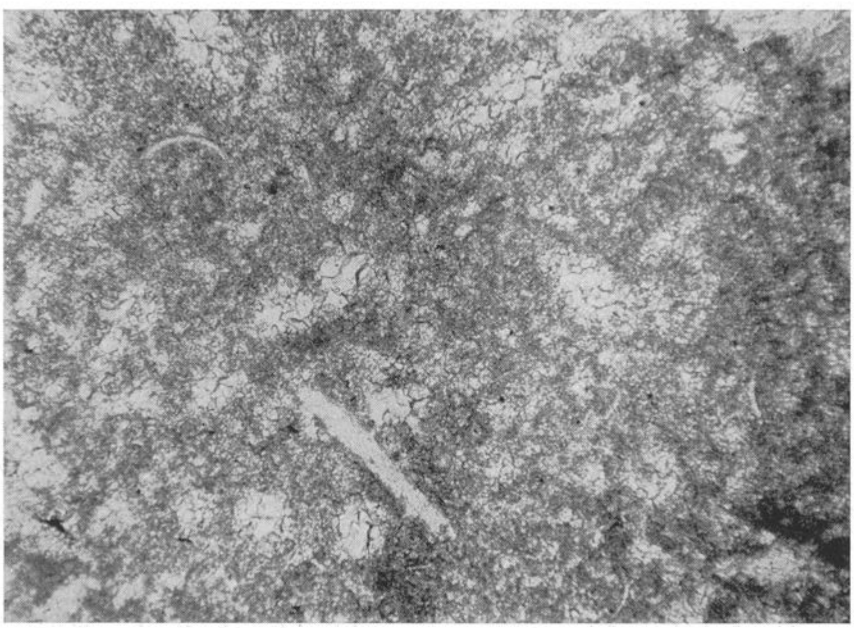


Fig. 170. Masur limestone. Flocky, partly cryptocrystalline, partly microcrystalline. Upper Ordovician. Erratic block. Brunnby, Öland. (Prep. 6526, photo 1766.) — 20 ×.

Diagenesis: Complete recrystallization of fossil fragments, less of matrix.
Formation: Algal limestone formed in mud-free, shallow water.

Masur limestone, Brunnby.[1]

Macro: Light-grey, dense, knobby limestone, closely resembling the Masur limestone of Dalarna. No macrofossils have been observed. Weathering-crust light-brown or yellow.
Micro: Partly cryptocrystalline (grains <1 μ), flocculent (fig. 170), partly microcrystalline with clear grains (20—200 μ). Only a few, small fossil fragments.
Diagenesis: Incomplete crystallization.
Formation: Flocculent calcareous algae with extremely fine, pure calcareous mud deposited in quiet, shallow water.

The Upper Ordovician limestones of Östergötland.

We do not know of any continuous section through the Upper Ordovician strata of Östergötland. Small exposures occur in various places particularly at Vättern, west and south of Motala (J. Jönsson 1887, p. 20). Red Tretaspis shale crops out on Rödbergs udde, and farther to the south-west both black and red Tretaspis shale and Masur limestone have been observed in a now inaccessible section. Red fossiliferous Tretaspis marl with thin beds of red limestone crops out on Råsnäs udde, and blocks of Masur limestone are encountered there in such great quantity that this rock, too, must form part of the bedrock in the same place. The Tretaspis shale at Råsnäs is overlain by green shale and grey, knobby limestone, which (according to J. Jönsson 1887, p. 21) is occasionally found to be separated from the Tretaspis shale by a conglomeratic limestone with balls of Tretaspis marl. The knobby limestone probably belongs to the Tretaspis stage (cf. scheme on p. 231).

Masur limestone, Råsnäs udde.

Macro: Dense, greyish-green with bands and patches of brownish-red. Bed uneven, knobby, 4—6 cm. Brownish-red pelmatozoan fragments.
Micro: Flocculent, partly cryptocrystalline, partly microcrystalline limestone (grains 2—6 μ) with a few small ostracods, trilobite and pelmatozoan fragments (fig. 171).
Diagenesis: Slight crystallization of calcareous mud.
Formation: Sedimentation in quiet water without supply of coarse inorganic detritus. The cryptocrystalline parts may be formed by calcareous algae.

[1] Masur = knot in wood. Masur limestone may be used as a lithologic term for knobby limestones with dense texture and (probably) algal origin. The Masur limestone of Sweden is stratigraphically a Lower Tretaspis limestone = Slandrom limestone (Thorslund 1943, p. 6, note 3).

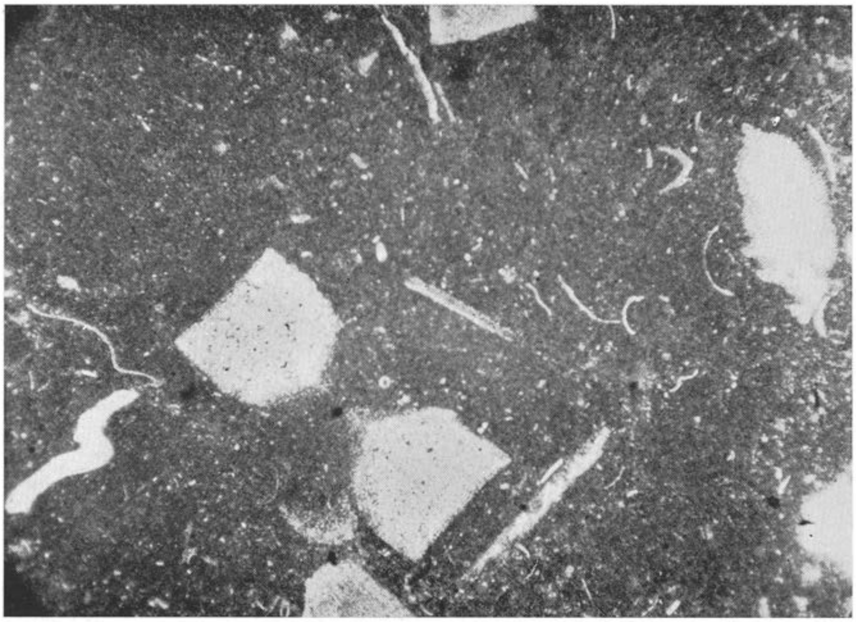


Fig. 171. Masur limestone, crypto- and microcrystalline. Tretaspis limestone, Upper Ordovician. Råsnäs udde, Östergötland. (Prep. 7785, photo 1701.) — 20×.

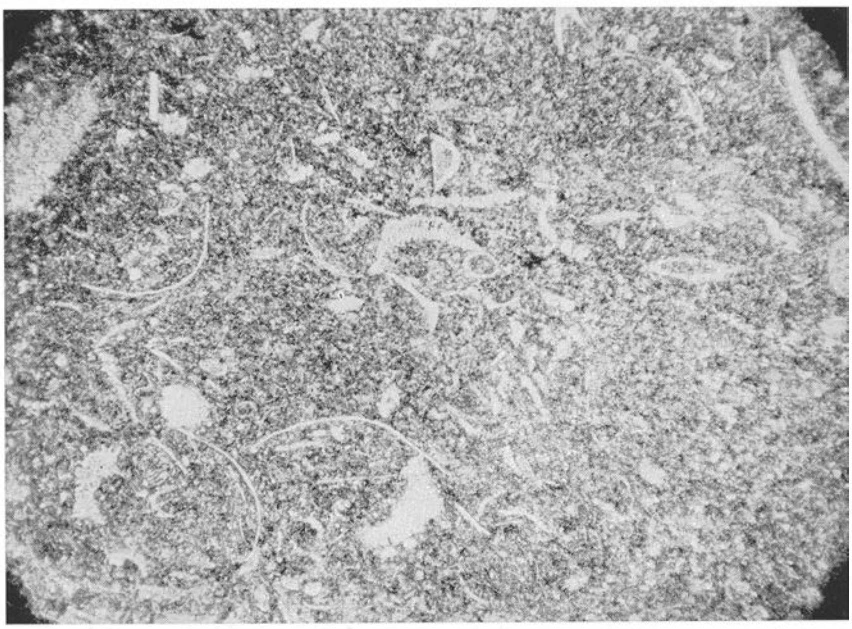


Fig. 172. Microcrystalline limestone, argillaceous and hematite pigmented, with microcoquina. Red Tretaspis limestone, Upper Ordovician. Råsnäs udde, Östergötland. (Prep. 7784, photo 1697.) — 20×.

Red Tretaspis limestone, Råsnäs udde.

Macro: Dense, brownish-red, marly, thin-bedded limestone with a few macrofossils (fragments of trilobites, ostracods, pelmatozoans).

Micro: Matrix of microcrystalline calcite (grains 2—5 μ) much blended with argillaceous matter and hematite dust and with abundant microcoquina (fig. 172). Extremely thin, small shells occur in great quantity. Larger fossil fragments only sparingly. Grains of quartz, 10—50 μ, irregularly interspersed in the sediment.

Diagenesis: Slight crystallization of calcareous mud.

Formation: Sedimentation in quiet, shallow water. Oxidizing environment.

Oolitic limestone, S. Fredberga.

At the bottom of a gravel-pit by the Motala-Fågelstad railway in the vicinity of South Fredberga there is outcropping bedrock of grey Chasmops limestone, according to J. Jönsson (1887). From the same region originate a grey, marly shale which was collected by Törnquist, and also blocks of oolitic limestone. Although this limestone has not yet been encountered as solid bedrock and its age has not been definitely established,[1] it will be mentioned on account of its peculiar structure.

Macro: White, granular (fine-oolitic) limestone with a few macrofossils (simple coral of the type *Densiphyllum thomsoni* and thick-shelled brachiopod of the type *Orthis umbo*, according to Törnquist).

Micro: In a crystalline calcite matrix lie ooids of varying size and shape with radiated fibrous and often, too, concentric texture (fig. 173). The ooids generally have a core of crinoidal or shell fragments, clear calcite, or a dense algal-carbonate mass. The round ooids are seldom more than 0,6 mm in diameter; the elongated ones (with core of shell fragments) go up to 1,5 mm.

In the limestone there are scattered, greatly rounded nodules, of white, cryptocrystalline, strongly light-absorbing algal limestone. These nodules attain a diameter of 5 mm. Other, smaller, irregularly shaped nodules and grains consist of flocculent, porous calcareous algae. They occur in profusion.

Diagenesis: Thorough crystallization of the calcium carbonate of the matrix and ooids, slight crystallization of the porous algal nodules.

Formation: Deposition in shallow, warm, littoral water, without supply of inorganic detritus, probably near limestone reef.[2] The rounded nodules are worn fragments of a broken-up algal mat.

[1] The fossil fragments observed in the limestone (corals and brachiopods) seem to have led Törnquist (on label) to put the rock in the Tretaspis series, but with a note that its age is unknown. Cf. the oolitic limestone of the Dalmanitina series in Västergötland (see p. 238).

[2] The best-known occurrence of Ordovician reef limestone is found in Dalarna. The blocks may possibly originate from there. Oolitic limestone of the same nature as that described here, but more recrystallized, occurs in the upper part of the Dalmanitina stage of Västergötland. — See further p. 238.

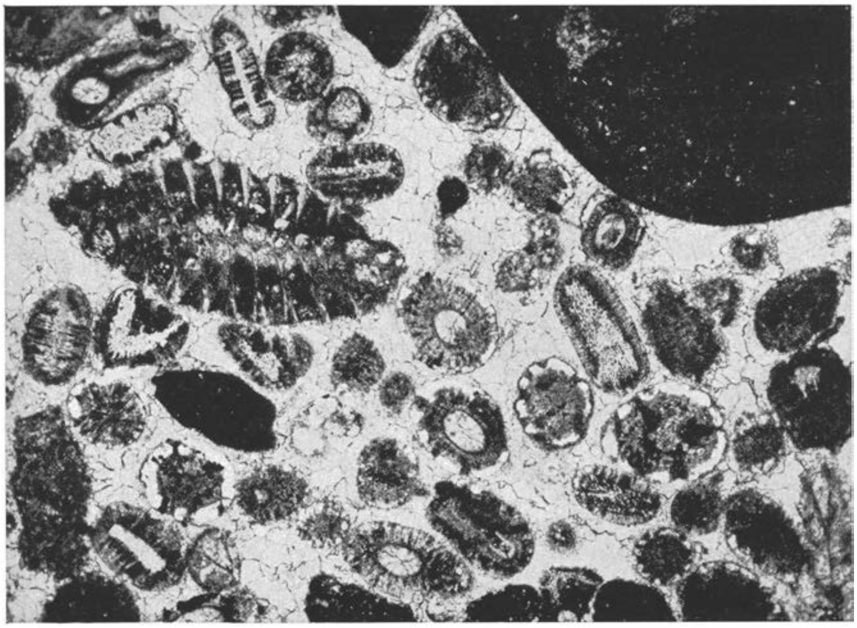


Fig. 173. Oolitic limestone with cryptocrystalline, algal nodules. Upper Ordovician. Erratic block. S. Fredberga, Östergötland. (Prep. 8798, photo 1630.) — 20×.

The Upper Ordovician limestones of Västergötland.

The Upper Ordovician of Västergötland consists of the Tretaspis and Dalmanitina series. Both contain at different levels more or less arenaceous and argillaceous limestones.

Limestones of the Tretaspis series.

The Tretaspis series is somewhat differently developed in different parts of Västergötland, but as a rule it comprises a lower division with black Tretaspis shale, a central with limestone (Masur limestone), and an upper with red Tretaspis shale. Nowhere is there a natural section through the whole series. The connection between the different divisions and their thickness is best illustrated by the core-drilling at Kullatorp on Kinnekulle. The Ordovician series of strata which follows upon the Chasmops series has been examined and described by Henningsmoen (1948, p. 374 ff.) and Waern (1948, p. 433 ff.). It comprises the following divisions (p. 231):

The only important limestone in the Tretaspis series, the Masur limestone, lies above the black and green Tretaspis shale. In Dalarna, where the Masur limestone has its greatest thickness and most characteristic development, it lies below the black Tretaspis shale. The lithological similarity between the Masur limestone of Dalarna and that of Västergötland indicates similar conditions of formation.

Upper Ordovician	Dalmanitina series[1]	Limestone with *Dalmanitina mucronata*, at the base conglomeratic		2,38 m
	Tretaspis series (27,85 m)	Sandstone[2]	Grey sandstone Greyish siltstone Greyish-green mudstone	2,65 m
		Red Tretaspis mudstone	Brownish-red mudstone, sometimes greyish-green	14,3 m
		Masur limestone	Grey, dense limestone	1,2 m
		Green Tretaspis shale	Greyish-green mudstone with limestone nodules	1,35 m
		Black Tretaspis shale	Dark marlstone Speckled shale Grey mudstone Black shale (2,0 m) Glauconitic marlstone (0,15)	8,35 m
Middle Ordovician (Chasmops series)		Black shale with graptolites Grey limestone and mudstone		

I have not had access to a specimen of the Masur limestone of Kinnekulle, and I am therefore happy to be able to quote the description of the rock given by HENNINGSMOEN (1948, pp. 379 and 385).

Masur limestone, Kullatorp, Kinnekulle (according to HENNINGSMOEN).

"A grey to dark-grey, dense limestone, irregularly intersected by fissures filled with calcite. (So-called *Masur* limestone.) The fissures were probably formed by contraction, as they do not seem to penetrate into the under- or overlying rock. Finely crystalline pyrite is not uncommon. The lower part of the limestone contains argillaceous partings, likewise the uppermost part. The limestone seems to consist of beds parted by irregular (corrosion?) surfaces." — "The limestone is fairly pure (90 % $CaCO_3$) and free from any coarse clastic material, thus indicating a deposition under quiet conditions. The limestone contains no macrofossils. This is rather astonishing, as it is a compact limestone where conditions for preservation should

[1] The Dalmanitina series is reckoned by WAERN (1948) as belonging to the Silurian.
[2] Probably a representative of the Staurocephalus zone (HENNINGSMOEN 1948, p. 376).

be good. Some (undetermined) microfossils seen in a thin section are of interest, since they show that if macrofossils had been embedded, they would not have been dissolved later on — small fossils usually being dissolved first. There could hardly have been any macrofauna of importance here during the deposition of this limestone. Even microfossils seem scarce. The limestone does not show evidence of organic origin. Such limestones are often said to be chemical deposits, though micro-organisms are probably playing an important part in the precipitation of the carbonates. Such processes are known to occur now in shoal-water areas and in lagoons. — Scattered minute crystals of pyrite tell of somewhat stagnant conditions. In harmony with this there seem to be corrosion surfaces in the limestone, probably telling of times with even higher acidity of the waters."

For the Masur limestone of Västergötland attention is also drawn to the following short description of the rock at Bestorp. The formation of the typical, very knobby limestone is discussed in connection with the report on the Masur limestone at Fjäcka in Dalarna (p. 244), a limestone which is interpreted by the author as an algal limestone.

Masur limestone, Bestorp.

Macro: Flint-dense, splintery, grey in different shades (partly reddish-grey and then not unlike "pink Baltic-sea limestone"). Macrofossils: carapaces of trilobites (*Illaenus* and *Remopleurides*), crinoidal fragments. Weathering-crust earthy, brown.

Micro: Grumous, crypto- and microcrystalline (grains 1—2 μ) with fine calcite veins (fig. 174). Scattered small fragments of shells and pelmatozoans. Light, cylindrical "worm-burrows".

Diagenesis: Very slight crystallization of calcareous mud.

Formation: Sedimentation basin with quiet water. Occasional washing-in of fragments. Reducing or neutral environment. Formation has taken place with the help of calcareous algae.

Red Tretaspis limestone, Skogastorp.

The Tretaspis series from Skogastorp on the north side of Högstenaberget is mentioned by LINNARSSON (1869, p. 48). In a brook-ravine the series is more readily accessible than anywhere else in Västergötland. He noted the following series of strata:

Shale with *Dalmanitina mucronata* etc. — Dalmanitina series

— — —

Hard, speckled, not easily split shale ("Staurocephalus shale")
Limestone, impure, irregular, approx. 0,5 m
Shales of varying colour: black, red, green, grey
Red Tretaspis shale, with limestone in lower part (concretions according to LINNARSSON)

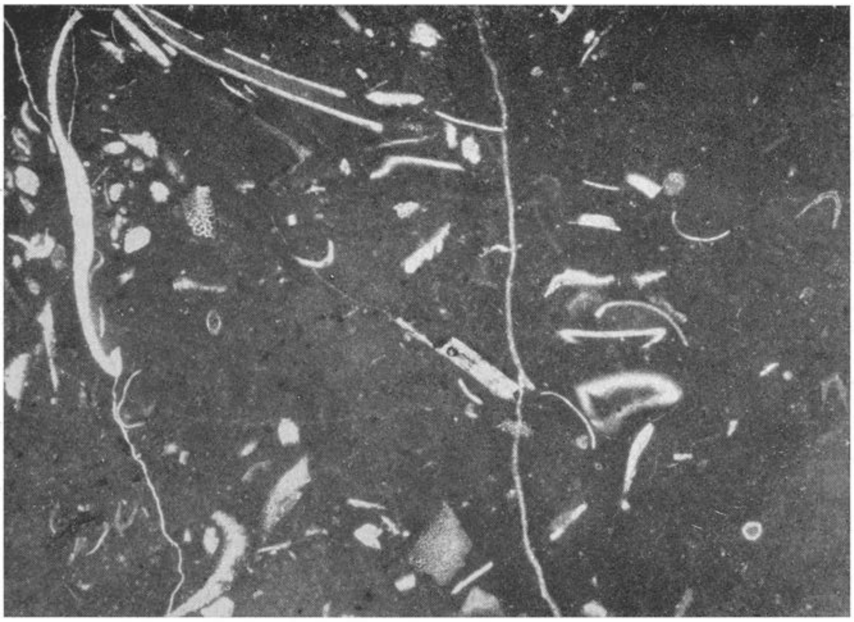


Fig. 174. Masur limestone, grumous, crypto- and microcrystalline. Tretaspis limestone, Upper Ordovician. Bestorp, Västergötland. (Prep. 2040, photo 1357.) — 20×.

Light-green Tretaspis shale, in lower part dark-green with yellowish-green bands and patches; the shale is red in patches

— — —

Limestone ("Beyrichia limestone") — Chasmops series

In several places in the red Tretaspis shale there are lumps and irregular, knobby bands of red limestone. The limestone mentioned by LINNARSSON is of the same type. The specimens of the limestone which have been available to the author were collected by J. A. WALLIN.

Macro: Dense, dull, greyish-red or brownish-grey limestone. Conchoidal fracture with sharp edges. Almost no fossils, only a few small fragments observed.

Micro: Microcrystalline calcite mass (grains 5—10 μ) with scattered angular grains of quartz (10—20 μ). Cryptocrystalline pigment. Pyrite crystals partly changed to limonite. — Prep. 8795.

Diagenesis: Crystallization of the calcite.

Formation: Argillaceous and calcareous mud together with fine-grained quartz deposited in quiet water. The mud was red primarily (before transportation to the site of deposition). Iron sulphide has been precipitated (in small quantity) at the site of deposition, so that a certain amount of reduction there has been possible.

Limestones of the Dalmanitina series of Västergötland.

In the Cambro-Silurian area of Sweden the Dalmanitina series has an appreciably smaller content of limestones than the underlying parts of the series of strata. The thick series of limestones of the Asaphus series and the marly layers with beds of limestone of the Chasmops series have been replaced in the Dalmanitina by shales, not infrequently arenaceous. In north Sweden sandstones (quartzites) dominate. These conditions have with justification been considered as indicating a shallowing of the sedimentation area, a period of regression. There is also direct proof that parts of the Dalmanitina series were deposited in very shallow water. We find it for example in the limestones included in the series, partly in the form of beds or reefs rich in calcareous algae, partly as intraformational conglomerates. The reef limestones of the Dalmanitina series (Upper Leptaena limestone) have been dealt with earlier (HADDING 1941); below a few types of the bedded limestones are discussed.

In LINNARSSON's classic description of the Cambro-Silurian of Västergötland (LINNARSSON 1869) mention is made of limestone in "brachiopod shale"[1] from several places, in most cases as coarse-grained, hard, grey limestone, approx. 1,5 m thick. It is interstratified in light-grey and dark-grey shale. LINNARSSON found the rocks to be particularly fossiliferous and well-developed on Ålleberg. The series was later examined by TROEDSSON. He reported (1921) the following section, which can be regarded as typical for the area:

Graptolite shale — Silurian	—
Shale, soft, non-calcareous with *Acidaspis centrina* DALM.	1 m
Shale, not very calcareous	1,2 »
Limestone, unstratified, hard, grey with *Ptychophyllum linnarssoni*, brachiopods, etc.	1,5 »
Shale, calcareous, thick-bedded, hard, — unweathered dense, grey, — weathered porous, brown	—

The limestone varies in thickness and is different in different places. It will be described below in three type-specimens from Ålleberg: coral limestone, conglomeratic limestone, and dense (algal) limestone. Additional specimens from other localities are mentioned as examples of the varying nature of the rocks.

Coral limestone, Dalmanitina series, Ålleberg.

Macro: Crystalline, grey with dense, greyish-brown portions. Numerous specimens of *Ptychophyllum linnarssoni* occur in the limestone, all of them overturned and unoriented but more or less parallel to the bedding planes. They have a length of 60 mm and a diameter of approx. 15 mm. Septaria are well preserved even in weathered, rust-coloured parts of the rock.

[1] The name "brachiopod shale" more or less meant the Dalmanitina series.

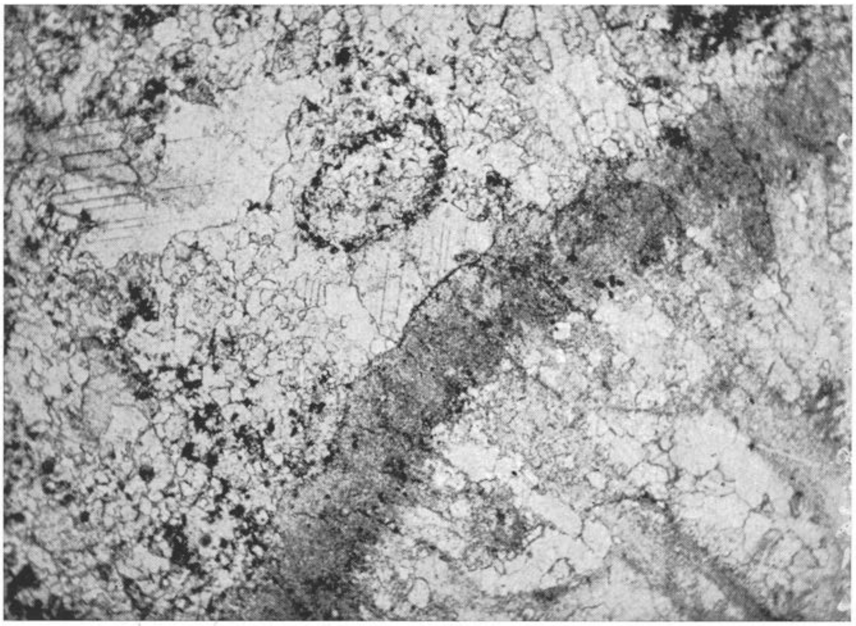


Fig. 175. Coral limestone, strongly recrystallized. Lower right shows a part of a coral skeleton. Dalmanitina limestone, Upper Ordovician. Ålleberg, Västergötland. (Prep. 8806, photo 1602.) — 20×.

Micro: Matrix and fossils extensively recrystallized to a granular mass, in which the macroscopically clear details (e. g. septaria) can hardly be distinguished (fig. 175). Grains of quartz, 0,02—0,05 mm, are fairly common.

Diagenesis: Temporary flourishing of coral fauna, with little or no supply of grains of sand. At times turbulent water, deposition of coarse detritus, and embedding of the corals which had fallen over when the fine argillaceous mud supporting them was washed away. As the individual coral bodies lie at different levels, flourishing and destruction of the corals must have occurred repeatedly.

Conglomeratic limestone, Dalmanitina series, Ålleberg.

Macro: In a microcrystalline, grey ground-mass there are profuse rounded, smooth, small pebbles (1—10 mm) and fossils, e. g. *Ptychophyllum*. Pyrite occurs in concretions of one centimetre. The weathering-crust is porous, rust-coloured, and like Backstein.

Micro: Matrix of crystalline calcite in clear grains, mostly less than 0,2 mm. Argillaceous pigment and grains of quartz are almost entirely absent. The pebbles consist chiefly of shale, more or less calcareous or arenaceous (quartz grains 10—40 μ). They are also of different density and colour, and they contain parts of different

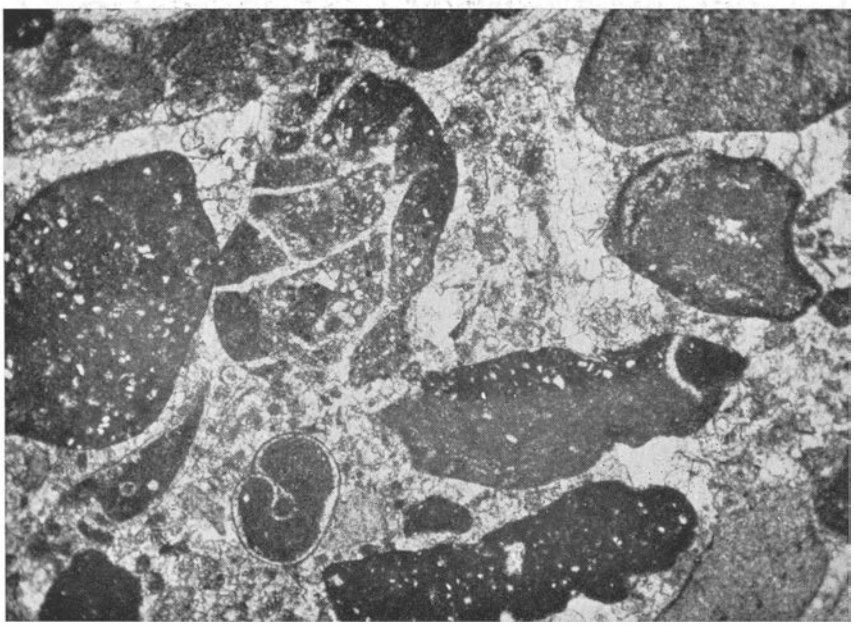


Fig. 176. Conglomeratic limestone. Dalmanitina limestone, Upper Ordovician. Ålleberg, Västergötland. (Prep. 7792, photo 1598.) — 20 ×.

layers (fig. 176). Greatly worn, rounded fossils (corals, bryozoans, and crinoids) occur among the pebbles. Many of the pebbles have a dark-pigmented peripheral zone.

Diagenesis: The calcareous mud in which the pebbles were embedded has been completely recrystallized after deposition.

Formation: The conglomerate pebbles have been formed in connection with negative sedimentation. The strata which were broken up are of varying nature, but they do not differ from the layers occurring in the older parts of the series of strata. What the pure (non-arenaceous and non-argillaceous) calcareous mud in which the pebbles were embedded was like and how it was formed is not apparent from the crystalline mass now forming the matrix. Shallow-water limestone.

Dense limestone, Dalmanitina series, Ålleberg.

Macro: Dense, hard, splintery limestone, grey with brown, porous weathering-crust (Backstein). No macrofossils have been observed.

Micro: The mass appears even-grained crystalline at slight magnification; at great magnification it proves to consist partly of a clear calcite aggregate with grains approx. 20 μ, partly of cryptocrystalline nodules, 30—60μ, occasionally with a border-crust of granular, clear calcite (fig. 177). The nodules are of the same nature as those described below in the algal limestone from Varnhem, and the crust can be interpreted as a faint beginning of an oolitic texture. Grains of quartz (approx.

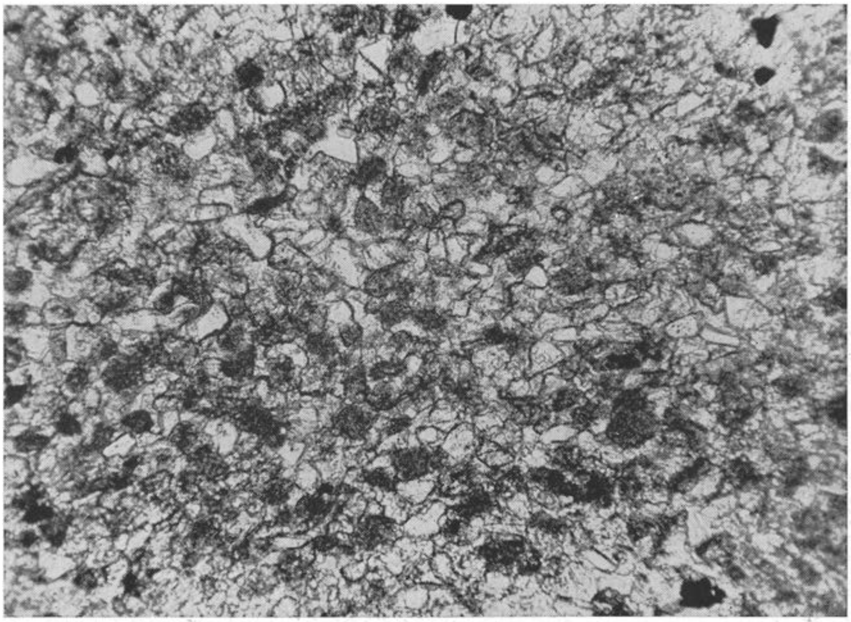


Fig. 177. Microcrystalline, arenaceous limestone with nodules (dark) of cryptocrystalline, algal calcite. Dalmanitina limestone, Upper Ordovician. Ålleberg, Västergötland. (Prep. 7795, photo 1716.) — 70×.

40 μ) occur fairly generally in the rock together with small fossil fragments. There is no pyrite.

Diagenesis: Clear recrystallization of the calcareous mud but none or very slight in the nodules (interpreted as calcareous algae).

Formation: Deposition of mud with well separated matter (uniform size of quartz grains and nodules) in shallow water.

Nodular, algal limestone, Dalmanitina series, Varnhem.

Macro: Microcrystalline, light-grey limestone with round, hazily circumscribed nodules. No macrofossils observed.

Micro: Ground-mass of relatively even-grained, fine-crystalline, clear calcite (grains 30—60 μ) enclosing patches (nodules) of considerably smaller grain-size (5—10 μ) and apparently darker colour (fig. 178). No fossil fragments or grains of quartz. Pyrite occurs in scattered small grains.

Diagenesis: Recrystallization, clear in the ground-mass, slight or unnoticeable in the nodules.

Formation: Calcareous mud deposited in shallow water, relatively non-argillaceous and free of coarse detritus. The dense, diffuse nodules are calcareous algae. (Cf. HADDING 1958.)

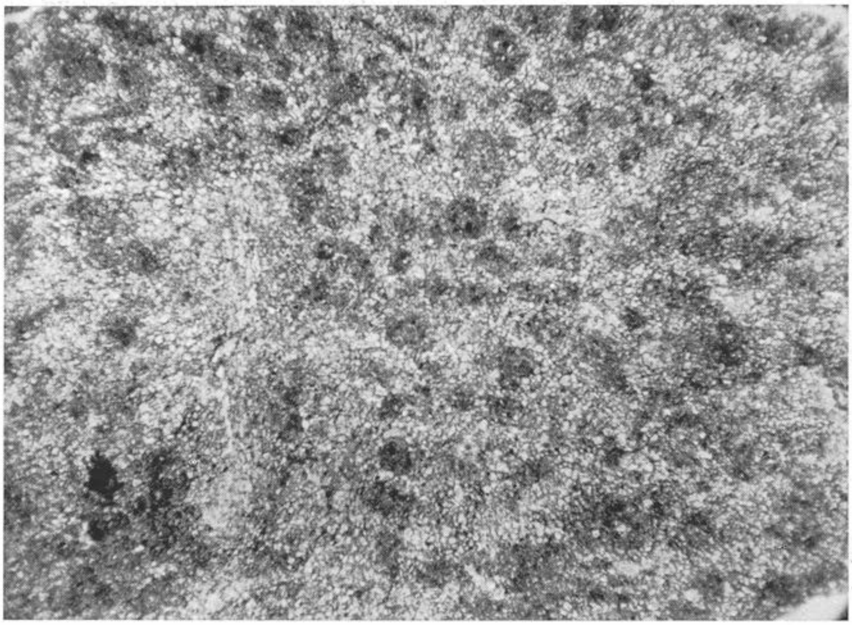


Fig. 178. Microcrystalline limestone with recrystallized, algal nodules. Dalmanitina limestone, Upper Ordovician. Varnhem, Västergötland. (Prep. 2540, photo 1715.) — 20×.

Oolitic limestone, Dalmanitina series, Skogastorp.

Oolitic limestone has been encountered in the upper part of the Dalmanitina stage on Plantaberget in Västergötland. This rock was observed by G. C. von Schmalensee at Kungslena as early as 1899.[1] Linnarsson (1869) and Troedsson (1921) describe a section at Skogastorp without, however, mentioning the occurrence of oolitic limestone. From the central part of the section they mention light-grey, thick-slabbed, calcareous shale. Specimens of this, collected by Troedsson, have proved to consist of oolitic limestone of the same type as that observed by von Schmalensee. However, it is less thoroughly recrystallized at Skogastorp. It will be described below.

Macro: Microcrystalline, grey limestone with scattered, one-millimetre-large, spathic, crinoidal fragments. The weathered surface, which is light grey, has small cavities from round grains (ooids) removed by weathering.

Micro: Matrix of crystalline calcite (grains approx. 30 μ), enclosing ooids, and much-worn pelmatozoan and shell fragments. The ooids are completely recrystallized

[1] The specimen collected by von Schmalensee is in the Geological Museum in Lund. The label, typical of von Schmalensee, reads in translation: "Oolitic calcareous sandstone, rock not further investigated — in upper part of the Brachiopod shale at Kungslena, Västergötland. 1899 v. Schm. — A slice has not been made and perhaps should be. — It would probably be more accurate to call the whole of the Brachiopod shale calcareous sandstone in closer conformity with Norway's stage 5 and Caradoc sandstone (?)."

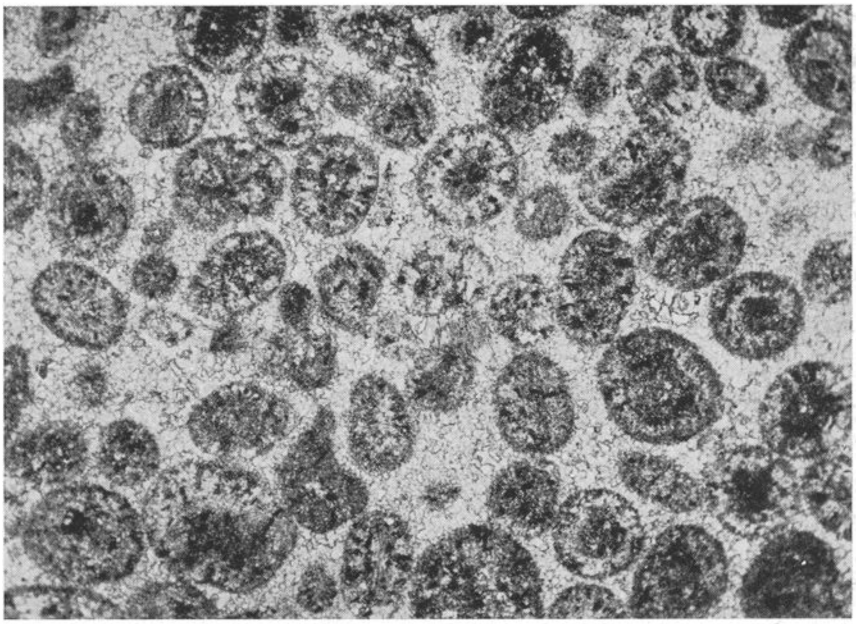


Fig. 179. Oolitic limestone, recrystallized. Dalmanitina limestone, Upper Ordovician. Skogastorp, Västergötland. (Prep. 8807, photo 1603.) — 20×.

but do show traces of concentric and radial fibrous texture (fig. 179). The core may consist of a fossil fragment but is oftener a diffuse grain of fine-grained calcite (3—5 μ), of the same nature as the small calcareous algal nodules in the abovementioned limestone from Varnhem. There are no grains of quartz and no pyrite.

Diagenesis: Clear recrystallization of matrix and ooids, but not of the algal core.

Formation: Ooid-formation in shallow water with deposition of calcareous mud and fossil fragments. Calcareous algae have taken part in the formation of the dense, diffuse core of the ooids. Grains of quartz and other inorganic detritus were not deposited in the sedimentation area during formation of the ooids.

Fragment limestone, Dalmanitina series, Gisseberg.

Macro: Crystalline, glistening, dark-grey limestone with numerous crinoidal fragments, best visible on weathered surface and in the reflecting calcite cleavages.

Micro: Matrix microcrystalline (grains 5—10 μ), with abundant small shells and crinoidal fragments (fig. 180). No grains of quartz. Pyrite occurs as a powder and as small grains, also in some of the fragments. A few phosphatic shells have been observed.

Diagenesis: Clear recrystallization.

Formation: Mixture of fragments and calcareous mud deposited in at times turbulent water. The pyrite-impregnated fragments originate partly from another environment.

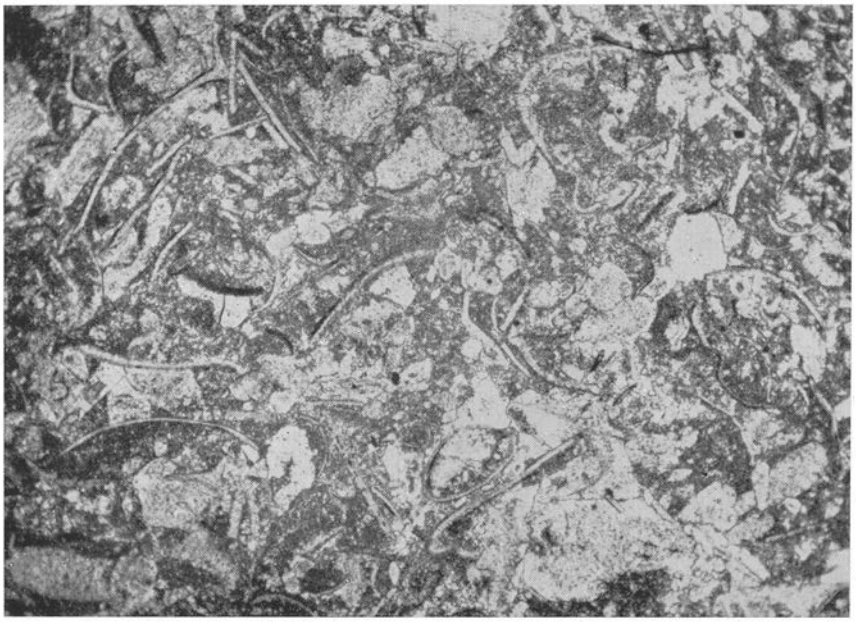


Fig. 180. Microcrystalline limestone with microcoquina. Dalmanitina limestone, Upper Ordovician. Gisseberg, Västergötland. (Prep. 7097, photo 1601.) — 20 ×.

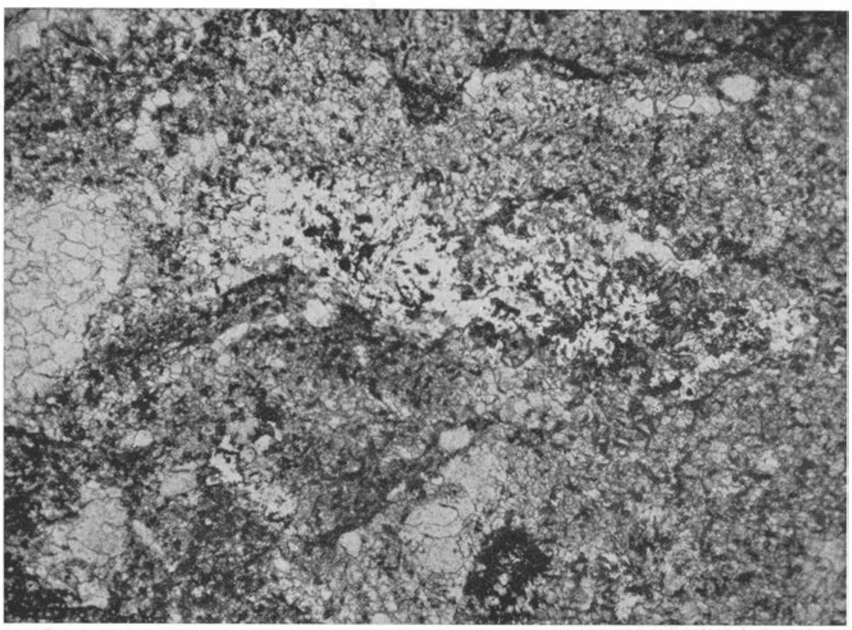


Fig. 181. Microcrystalline limestone, partly silicified (middle part). Dalmanitina limestone, Upper Ordovician. L. Lycke, Billingen, Västergötland. (Prep. 8809, photo 1600.) — 20 ×.

Silicified limestone, Dalmanitina series, L. Lycke, Billingen.

Certain limestones of the Dalmanitina stage of Västergötland are very much silicified. How the rock appears at an early stage of silification is shown by the specimen dealt with here.

Macro: Microcrystalline, white or light-grey limestone with small pores, secondarily filled with iron oxihydrate. No macrofossils observed.

Micro: Matrix of granular, clear calcite of varying coarseness (grains 0,05—0,25 mm). The calcite is interlarded with small flocks (spools) of a cryptocrystalline argillaceous substance. Grains of quartz (less than 0,1 mm) occur only sporadically. Secondarily formed silica occurs in irregular portions or in lenses parallel to the bedding planes (fig. 181). Around the lenses of submicroscopic chalcedony there are here and there coarser grains or needles. Silicification has occurred with only negligible displacement of the dark (argillaceous) substance. No trace of fossils has been found.

Diagenesis: Recrystallization of the calcareous mud and later silicification.

Formation: Deposition of mud in quiet water without supply of any appreciable quantity of quartz grains. It is not clear from the composition of the limestone whether silicification was made possible by siliceous organisms intermingled in the sediment or by pyroclastic matter.

Cordierite limestone, Dalmanitina series, Öglunda, Billingen.

Macro: Dense, hard, splintery, dark-grey, faintly glistening limestone with nodular, light-grey weathering-zone. No fossils observed.

Micro: Microcrystalline calcite (grains approx. 30 μ) and flocculent argillaceous matter. Lighter portions are formed by cordierite crystals, chiefly pseudohexagonal penetration-twins, enclosing argillaceous matter and surrounded by calcite (figs. 182, 183 a—b). No grains of quartz.

Diagenesis and metamorphism: Crystallization of the calcareous mud during flocculation of the argillaceous substance. The cordierite crystals have been formed by metamorphism influenced by the dolerite covering the sediments on Billingen.

Formation: The limestone was formed primarily by deposition of calcareous and argillaceous mud in shallow and relatively quiet water.

The Upper Ordovician limestones of Dalarna.

The Upper Ordovician series of strata of Dalarna recalls those of Östergötland and Västergötland. Törnquist (1883) gave the following sequence (partly rewritten):

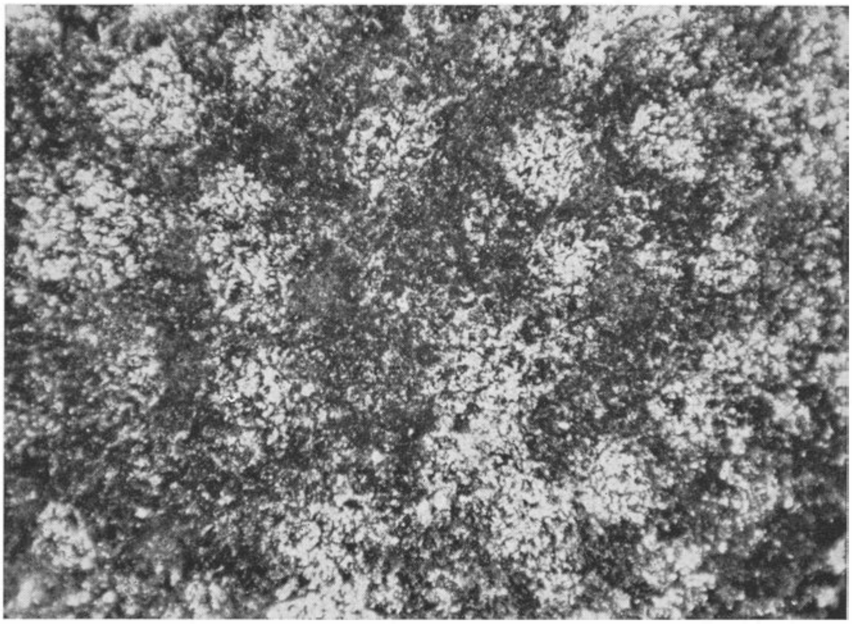


Fig. 182. Argillaceous limestone with cordierite crystals in aggregates of calcite. Dalmanitina limestone, Upper Ordovician. Öglunda, Västergötland. (Prep. 7301, photo 1705.) — 20×.

Upper Ordovician	"Klingkalk" (Clink limestone) — presumably belonging to the Dalmanitina series
	— — —
	Red Tretaspis shale, very calcareous, approx. 15 m
	Grey limestone, 4,5—9 m
	Black Tretaspis shale, 6 m
	Masur limestone, 9—15 m
	— — —
	Chasmops limestone — Middle Ordovician

However, the series of strata of Dalarna also includes reef limestones (cf. Hadding 1941). Reef-formation began during the Middle Ordovician and was concluded in the Dalmanitina series. The fragment limestones which were deposited about the reefs have a different environmental character from the rocks mentioned above.

A modern investigation of the lower half of the Tretaspis series has been carried out by Jaanusson and Martna (1948, p. 186). The investigation was made at Fjäcka and the following extracts are given of the result:

"*Middle Tretaspis limestone*", 2 m+. Argillaceous limestone, greenish-grey, with trails and nests of green marl.

Black Tretaspis shale, 5,8 m

Slandrom limestone, 8,4 m. Alternating fine-grained or nearly compact, argillaceous limestone and Masur limestone.

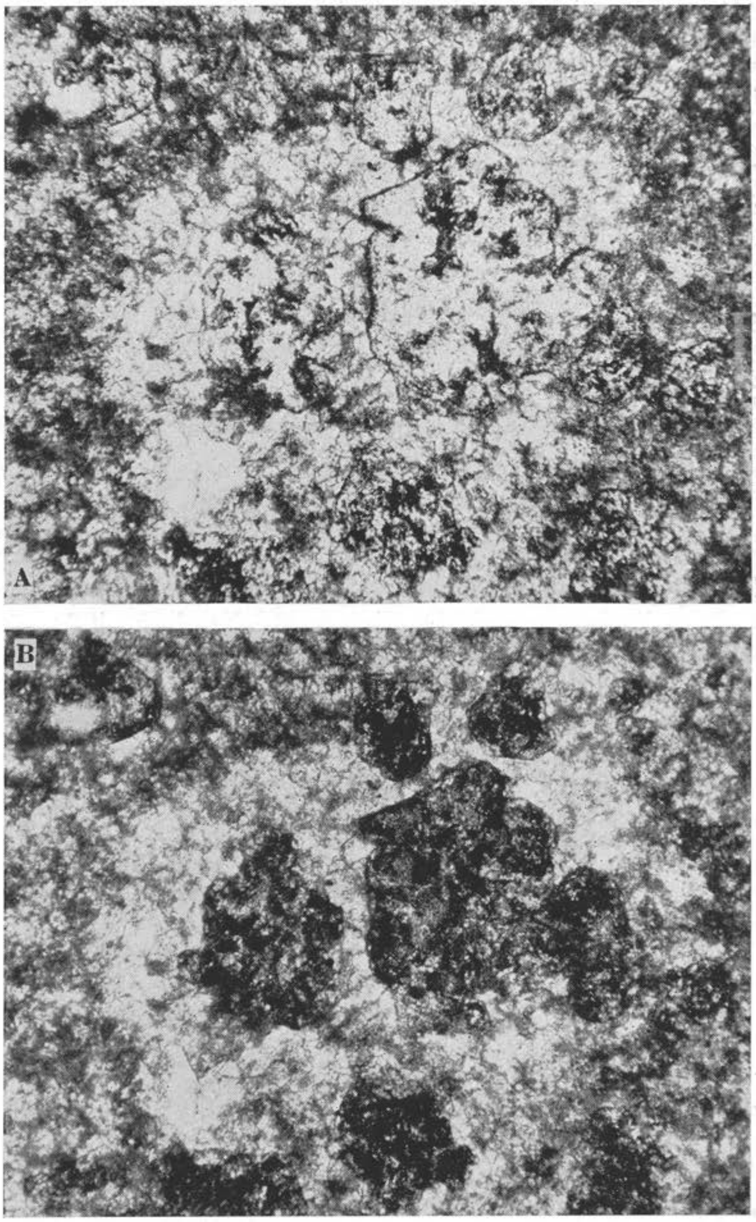


Fig. 183. Cordierite crystals in calcite aggregate. A) Nic. ||, B) Nic. +. Dalmanitina limestone, Upper Ordovician. Öglunda, Västergötland. (Prep. 7301, photo 1770 and 1771). — 90×.

The Masur limestone, the limestones enclosed in the shales, and the "Kling" limestone will be described below. Examples will also be given of bedded limestones which occur adjoining the reefs.

Tretaspis limestone of Dalarna.

Masur limestone, Fjäcka.

Lower Tretaspis limestone.

Macro: Bed approx. 4 cm. Flint-dense, light-grey and light greyish-brown limestone, very knobby and with fine cracks. Macrofossils extremely rare, but thin, dark cylindrical "burrows" occur abundantly. Irregular marlfilled cracks cause the limestone to fall apart into small lumps (fig. 184).

Micro: Flocculent, cryptocrystalline or extremely fine-crystalline limestone (grains 1—3 μ) (fig. 185). Pyrite occurs sparsely in small grains. Bitumen has been observed in small quantity, especially in the cracks. Fossil fragments exceptional.

Diagenesis: Very slight crystallization of the calcium carbonate. Cracking in connection with crystallization.

Formation: Fine calcareous mud, precipitated organically or chemically and deposited in quiet water together with a small quantity of argillaceous matter, may form a dense limestone with the same texture as the rock described here. It should, however, have sedimented in even, flat, relatively homogeneous beds, like lithographic limestone. The irregularly formed knots and very knobby beds of Masur limestone cannot be explained as normally sedimented calcareous mud. (The even-bedded limestone alternating with the Masur limestone has been formed in this way, on the other hand). The Masur limestone recalls parts of the calcareous algal reefs, and presumably it has been formed by calcareous algae as irregular mats or knobby layers. It has not, however, been possible to point out any trace of organic structure. The blurred or flocculent structure is, nevertheless, of the same kind as in certain dense algal limestones (Hadding 1958).

Tretaspis limestone, Fjäcka.

Alternating with Masur limestone at Fjäcka is a thin-bedded, somewhat marly limestone. The following was noted concerning a bed of 3 cm:

Macro: Dense, rather loose, marly, light-grey with greyish-yellow weathering-surfaces. Splintery fracture.

Micro: Microcrystalline (calcite grains 2—8 μ), with abundant microcoquina (<0,2 mm). A few larger fragments, e. g. *Tretaspis*. Abundant argillaceous matter, slightly brown-coloured (prep. 7308).

Diagenesis: Recrystallization of the calcium carbonate.

Formation: Deposition of calcareous and argillaceous mud in quiet water. Neutral environment.

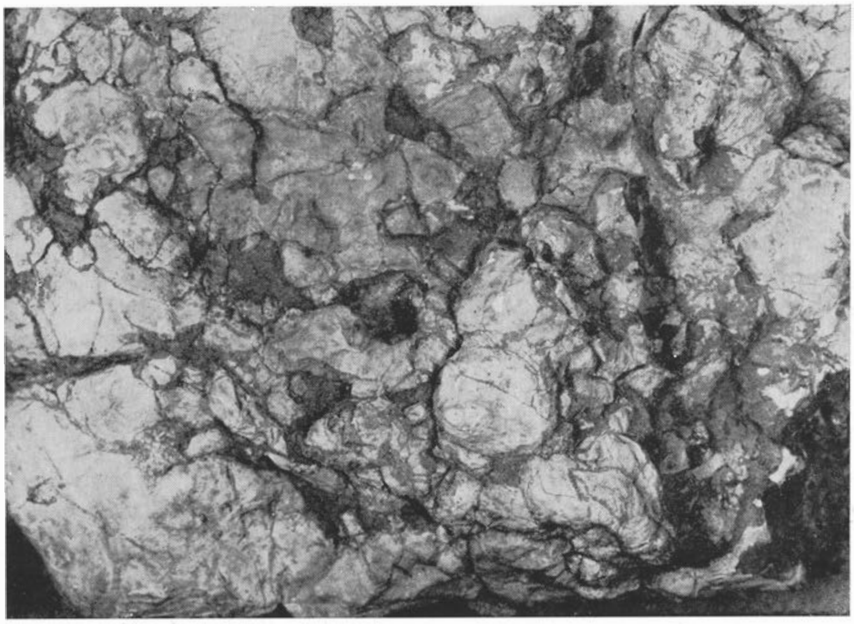


Fig. 184. Masur limestone, knobby, cracked. Upper Ordovician. Gulleråsen, Dalarna. (Photo 1791.) — $^{1}/_{1}$.

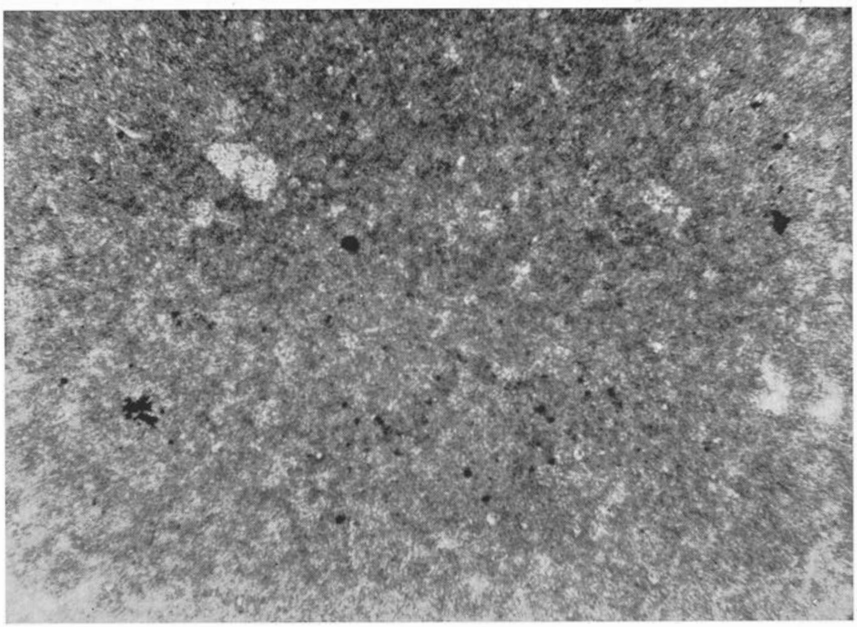


Fig. 185. Masur limestone, crypto- and microcrystalline, flocculent. Upper Ordovician. Fjäcka, Dalarna. (Prep. 7306, photo 1710.) — 70×.

Tretaspis limestone, Amtjärn.

Together with black Tretaspis shale, which overlies reef limestone ("Leptaena limestone") at Amtjärn, there are argillaceous, very bituminous limestone beds. An 8-cm-thick bed, with no visible stratification but splitting readily along accumulated carapaces of trilobites and shells of brachiopods, exhibited the following characteristics:

Macro: Fine-grained — dense, rather loose but splintery and cracked, dark greyish-brown, almost black. No pyrite.

Micro: Microcrystalline (grains 20—50 μ) with clear calcite crystals, displacing the dark-brown bituminous and argillaceous matter. Trilobite and brachiopod fragments occur abundantly, but they are largely very corroded. A crust of radiated calcite has been preserved even when the shell has disappeared (fig. 3, p. 12). Certain portions contain abundant pelmatozoan fragments.

Diagenesis: Dissolving of calcareous fragments and recrystallization with separation of the mud into pure calcite grains and bitumen + argillaceous matter.

Formation: Calcareous and argillaceous mud and organic matter deposited in quiet water. Open water, in which a fauna of trilobites has developed.

Stratified limestone surrounding the reefs, Dalarna.

The reef limestones of Dalarna lie as thick lenses in a stratified series of limestones and shales. The reefs are of different ages: the oldest belong to the Upper Chasmops and Lower Tretaspis series, the youngest to the upper part of the Tretaspis series and the lower part of the Dalmanitina series. (Isberg 1917, Warburg 1925, Thorslund 1936). The fauna is, of course, characterized by time, and so probably is the flora, too. In their general character, however, the reefs are essentially characterized by environment. They are largely composed of calcareous algae (Hadding 1941), with a distribution greatly limited by external conditions.

The bedded limestones surrounding the reefs were formed contemporaneously with them. They have arisen through accumulation of fragments from the reefs and the organisms which lived on or near them. In this way the bedded limestones, too, acquire a special character. Sedimentation on the flanks of the reefs has varied (Isberg 1917); shales and marlstones alternate with limestones. The latter are always fragment rocks and have particularly abundant pelmatozoans. A few of the rocks will be dealt with together here, irrespective of their different ages.

Pelmatozoan limestone, Amtjärn.

Beneath the black Tretaspis shale there are several beds of pelmatozoan limestone, mostly belonging to the Chasmops series. The marly types contain relatively long stem-fragments and whole brachiopod shells; the purer types consist of smaller fragments, washed clean and closely packed (fig. 186). The colour is sometimes green, sometimes red.

Bituminous fragment limestone, Kullsberg.

Above the oldest reef lens at Kullsberg a black, bedded limestone was observed.

Macro: Black, crystalline, disintegrating easily on impact, with abundant fossils; especially prominent are large carapaces of trilobites (*Illaenus*).

Micro: Crystalline, bituminous fragment limestone threaded with fine cracks. The crystals of the matrix-calcite are 0,2—0,6 mm. The bituminous matter is accumulated in the cracks and in or around the fossils (fig. 187). Fragments of trilobites, ostracods, pelmatozoans, and bryozoans. No pyrite.

Diagenesis: Thorough recrystallization.

Formation: Calcareous mud and abundant organic matter deposited in open, shallow water.

Crinoidal limestone, Osmundsberget.

Belonging to the Tretaspis series, according to Törnquist.

Macro: Grey fragment limestone, almost entirely composed of crinoidal stem fragments and scattered shells of brachiopods (*Sowerbyella*?). Matrix dark, bituminous, in small quantity only.

Micro: Rather coarse calcite joins the crinoidal fragments into a crystalline mass (fig. 188). The small bitumen-content is found as a thin coating on fossils and calcite crystals. No inorganic, coarse detritus. No pyrite.

Diagenesis: Thorough recrystallization.

Formation: The coarse fossil fragments have been accumulated in turbulent, shallow water without supply of inorganic detritus.

Fragment limestone, Osmundsberget.

Macro: Crystalline, brown-mottled fragment limestone with pelmatozoan and shell fragments.

Micro: Clear calcite occupies the whole of the space between the pelmatozoan fragments (1—2 mm), ostracods (0,5—1,5 mm), bryozoans (0,5—3,0 mm), and trilobite fragments (fig. 189). In certain pelmatozoans a dark pigmentation is noted. Otherwise, no impurities are seen in the limestone. (According to an analysis it contains 97,71 % $CaCO_3$ and 0,8 % substance insoluble in HCl).

Diagenesis: Thorough recrystallization.

Formation: Accumulation of pelmatozoans and other fossil fragments beside reefs.

Coral limestone, Dalmanitina series, Boda.

Together with compact, crystalline reef limestone coral stocks (*Sarcinula* (*Syringophyllum*) *organum*) occur locally embedded in mudstone. A specimen of this limestone from the Dalmanitina series at Boda has been examined.

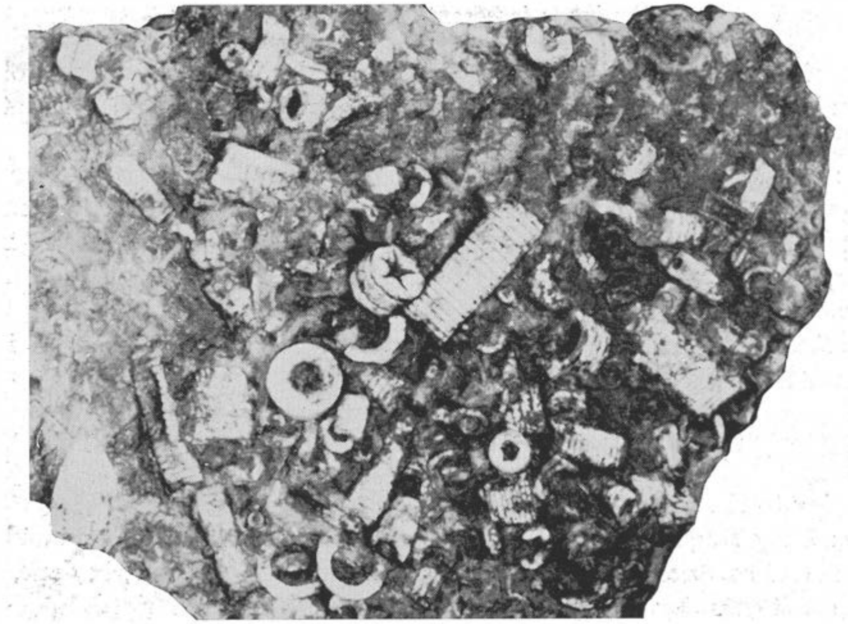


Fig. 186. Pelmatozoan limestone, thin-bedded, argillaceous. Chasmops limestone, Middle Ordovician. Amtjärn, Dalarna. (Photo 1792.) — $^1/_1$.

Fig. 187. Fragment limestone, bituminous, with trilobites, ostracods, and bryozoans. Tretaspis(?) limestone, Upper Ordovician. Kullsberg, Dalarna. (Prep. 4741, photo 1703.) — 20×.

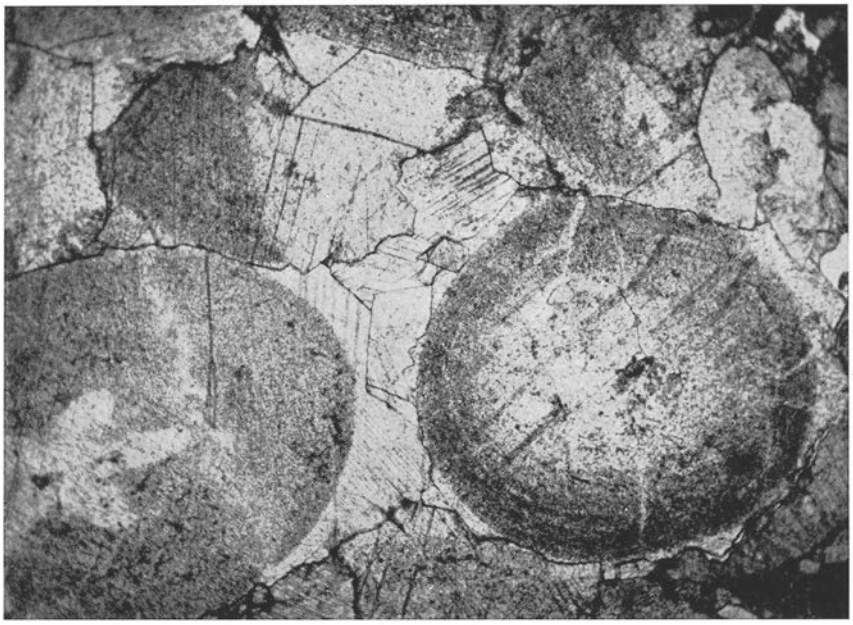


Fig. 188. Crinoidal limestone. Upper Ordovician. Osmundsberget, Dalarna. (Prep. 8796, photo 1654.) — 20×.

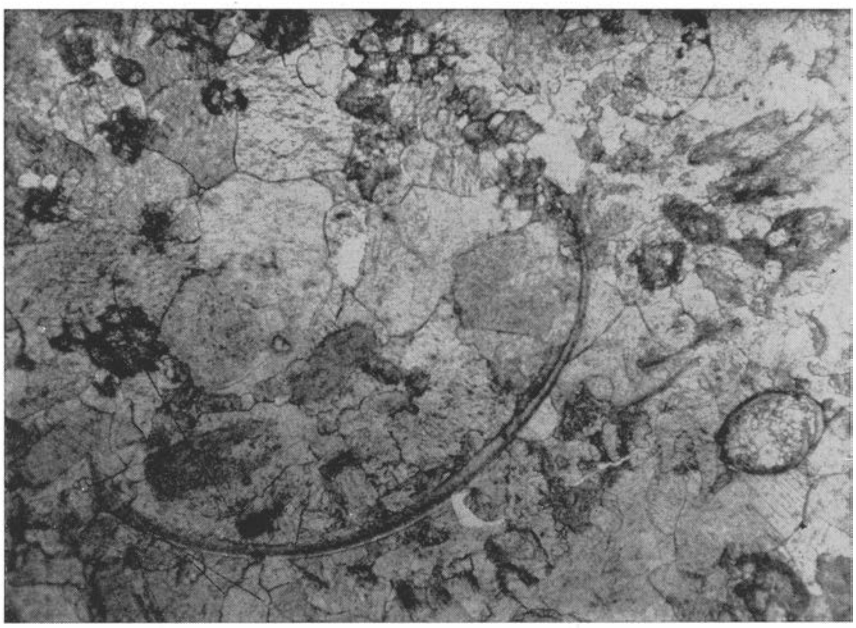


Fig. 189. Fragment limestone. Upper Ordovician. Osmundsberget, Dalarna. (Prep. 4727, photo 1702.) — 20×.

Fig. 190. Coral limestone with bituminous matrix. Upper Ordovician. Boda, Dalarna. (Prep. 3905, photo 1436.) — 20×.

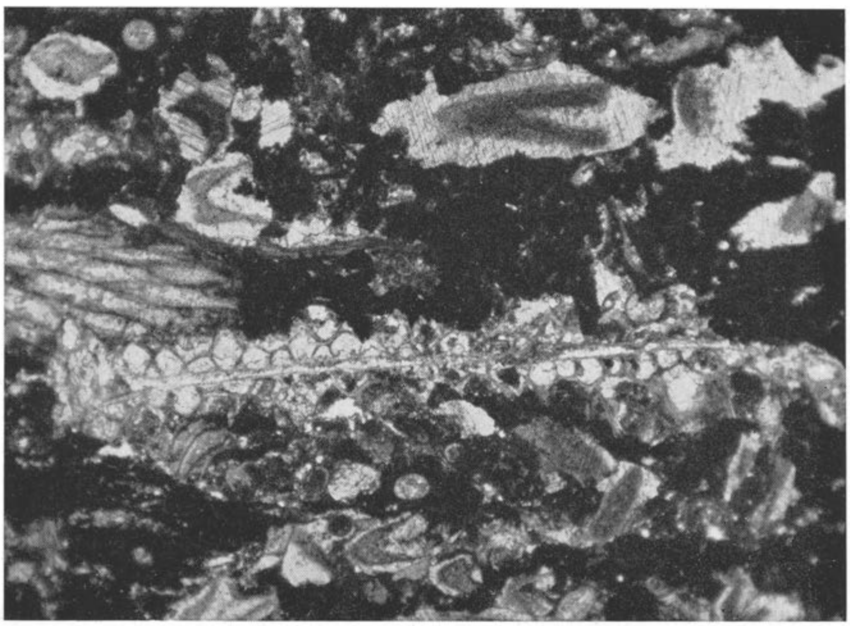


Fig. 191. Clink limestone ("Klingkalk") with dense, algal matrix and fragments of trilobites, crinoids, and bryozoans. Dalmanitina limestone, Upper Ordovician. Skattungbyn, Dalarna. (Prep. 6891, photo 1714.) — 20×.

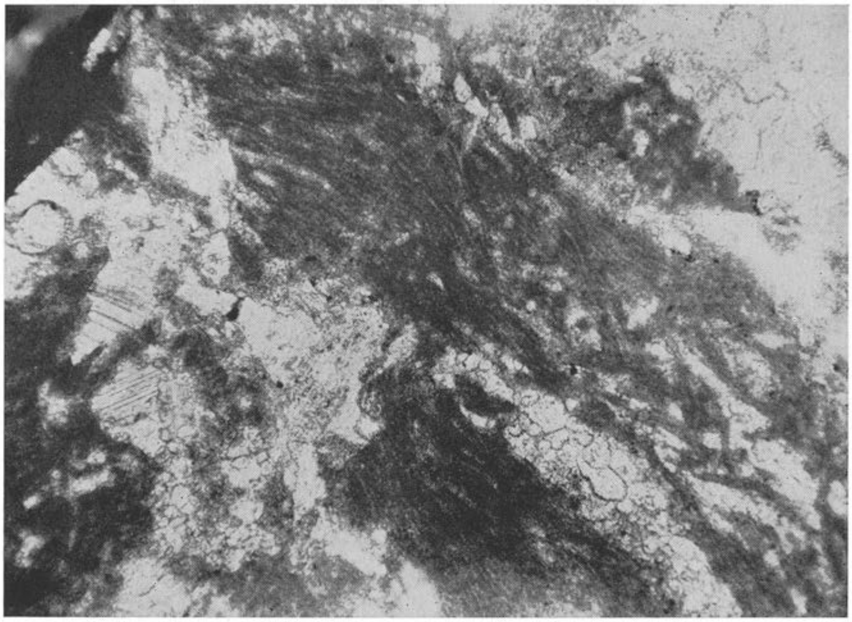


Fig. 192. Clink limestone. Matrix with fibrous algae. Dalmanitina limestone, Upper Ordovician. Skattungbyn, Dalarna. (Prep. 6891, photo 1768.) — 90×.

Macro: Dense, dark-brown mass with small fragments fills the space between the parallel coral cylinders of crystalline calcite.

Micro: The matrix is microcrystalline (grains approx. 0,01 mm) and coloured brown with petroleum or asphaltum, fairly uniformly distributed in the calcite aggregate. The mass is interlarded with small but thick shells of brachiopods (fig. 190) and a few crinoidal fragments. Traces of fine microcoquina, completely recrystallized, can be distinguished in the mass.

Diagenesis: Complete recrystallization of coral stock and brachiopod shells during formation of relatively coarse-grained calcite aggregate. The matrix (the calcareous mud) has crystallized without displacing the bituminous substance.

Formation: Calcareous mud deposited in shallow, quiet water close to algal limestone reefs. The bitumen-content has originated secondarily through infiltration of petroleum.

Algal limestone, Dalmanitina series, Skattungbyn.

"Klingkalk" (Clink limestone).

Macro: Light-grey, dense, with scattered, glistening grains. A few macrofossils: trilobites and brachiopods. When struck, clinking.

Micro: Matrix of submicroscopic calcite in a cloudy, not very transparent aggregate. Between crossed nicols the aggregate exhibits high double refraction without

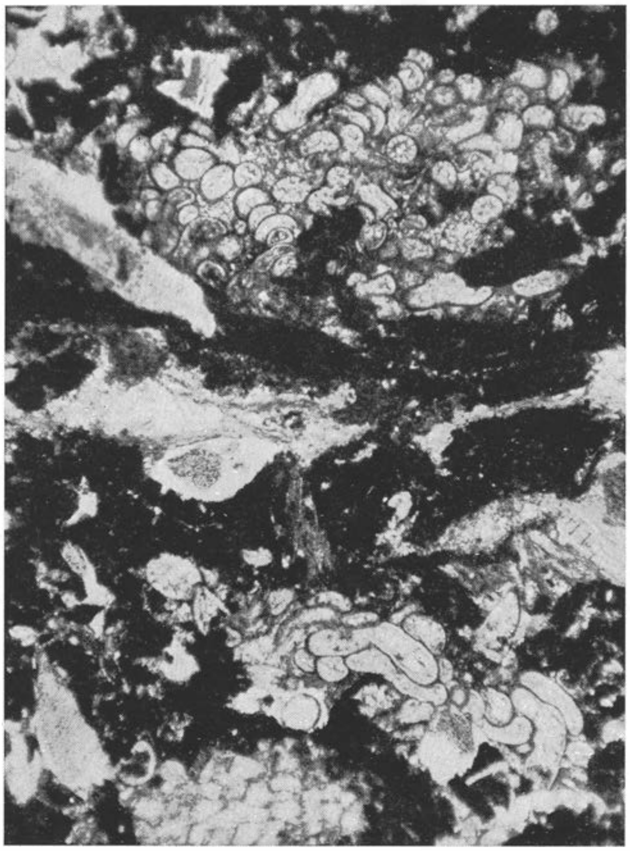


Fig. 193. Clink limestone. Dense, fibrous algal matrix (dark), and coarser algal threads and cells. Crinoidean and bryozoan fragments. Dalmanitina limestone, Upper Ordovician. Skattungbyn, Dalarna. (Prep. 6891, photo 1711.) — 20×.

extinguishing. The mass appears dense on slight magnification (fig. 191). On closer examination under high magnification the mass displays a fibrous development (fig. 192). The rock is an algal limestone of the same type as that we find in several places formed by green algae. In the ground-mass there are also abundant calcareous algae of another type, most closely related to the *Pilotrix* known from the Silurian strata of Gotland (HADDING 1941, p. 38). The alga appears chiefly in irregular lumps, but also as coating on shells (fig. 193).

In the algal mass there are scattered small fragments of crinoids, secondarily enlarged with clear calcite, a few bryozoans, and brachiopods.

Diagenesis: Coarse-crystalline calcite has been formed about the crinoidal fragments and in pores in the rock. Bryozoans and Pilotrix-algae are filled with fine-grained calcite aggregates of secretion-like structure. The cryptocrystalline algal mass shows no trace of diagenetic change.

Formation: There have been favourable conditions in warm, pure, shallow water for a flourishing of calcareous algae. The washing-in of crinoidal and bryozoan fragments together with brachiopod shells shows that the sedimentation site has been open to waves and tidal currents. The Clink limestone may be lagoonal and have been formed contemporaneously with the surrounding reef limestones.

Post-Ordovician limestones.

The post-Ordovician limestones of Sweden have a more limited distribution than the Ordovician. However, they have several forms which display a different lithological development. Silurian limestones occur in both Northern and Southern Sweden, and especially on Gotland. The more recent geological periods are poorly represented. The Middle and Upper Paleozoic are missing entirely, and the relatively unimportant series of the Lower and Middle Mesozoic contain no limestones. The Cretaceous system, on the other hand, is represented by thick limestone series, which, however, are confined to a small area of southernmost Sweden.

The author intends, in a forthcoming work, to give an account of the post-Ordovician limestones. He hopes, at the same time, to be able to make a summarizing survey of the Swedish limestones, their lithological character, formation, and importance as geological documents. A comparison will be made with some non-Swedish limestones, and, in connection with this, the systematization and nomenclature of the rocks will be discussed.

References.

Abbreviations.

BGU = Bulletin of the geological institution of the University of Upsala.
DGF = Meddelser fra Dansk Geologisk Forening. Köbenhavn.
DGU = Danmarks geologiske Undersögelse. Köbenhavn.
GFF = Geologiska föreningens förhandlingar. Stockholm.
KFS-H = Kungl. Fysiografiska sällskapets handlingar. N. F. Lund. 4°.
(Also: Lunds Universitets årsskrift.)
KFS-F = Kungl. Fysiografiska sällskapets förhandlingar. 8°.
KVA = Kungl. Vetenskapsakademien. Stockholm.
LGF = Lunds geologiska fältklubb. Lund.
LGI = Lunds geologiska institutioner (mineralogisk-paleontologisk-kvartärgeologiska). Lund.
LGMI = Lunds geologisk-mineralogiska institution. Lund.
SGU = Sveriges geologiska undersökning. Stockholm.

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Index.

*See the note of the figure.

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V. On the organic remains of the limestones. 1933. 5:50.
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