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THE PRE-QUATERNARY SEDIMENTARY ROCKS OF SWEDEN

BY

ASSAR HADDING

VI.

REEF LIMESTONES

WITH 88 FIGURES IN TEXT

LUND
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Preface.

The sedimentary rocks as a rule contain organic as well as inorganic material. In some of them, e. g. in sandy or clayey rocks, the inorganic clastic material takes up most of the mass, in others the organic material dominates. Among the latter the limestones are beyond comparison commonest and occur in the largest quantities.

A systematic division of the sedimentary limestones can be made upon different principles, e. g. upon their proportion of detritus or upon the calcareous organisms which have formed the rock. Also structural peculiarities can serve as basis for a division. The composition of the rock as well as its structure is, however, impressed by the milieu of development, and this would no doubt be the best basis for the geological and petrological description of the calcareous sediments. A future systematic analysis of the sediments ought to consider this idea. But our present knowledge of the calcareous sediments must first be deepened and therefore it seems to me most convenient to treat the limestones here without regard to a future division.

The author has chosen to segregate the structurally and paleontologically well defined reef limestones for a special investigation. The cause of that lies not only in the peculiar character of these limestones but also in the fact that in Sweden they are represented by three each very instructive types of different ages: the coral limestone in the youngest Cretaceous of Scania, the stromatoporoidal and coralline reefs in the Silurian of Gotland, and the algal reefs in the Ordovician-Silurian sedimentary series of Dalecarlia. It has not been possible to give the same space to all three types. The Cretaceous reefs are at present not exposed in Sweden, and like the Ordovician-Silurian reefs they are relatively unitary. They have therefore been treated more summarily, and especially for a comparison with the Gotland reefs. The latter are particularly numerous, well exposed and richly

varying. They have quite naturally been the object of investigation more than the others.

I wish to express my thanks to my friend Dr. J. E. Hede for many valuable discussions on the Silurian of Gotland and for his reading of the translated manuscript and the proofs. I want to thank Miss Ingrid Nilsson for her help with the photographs, the manuscript, the proofs, etc.

VI.

REEF LIMESTONES

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SILURIAN REEFS OF GOTLAND.

The series of strata in which the reefs of Gotland occur has of old attracted the interest of the geologists and has repeatedly been the subject of a more or less detailed discussion in geological literature, for instance by W. HISINGER, R. I. MURCHISON, FR. SCHMIDT, G. LINDSTRÖM, W. DAMES, H. MUNTHE, H. HEDSTRÖM, E. C. N. VAN HOEPEN, J. E. HEDE, etc. The reefs, however, have more seldom been the object of a special investigation (C. WIMAN, CROSFIELD-JOHNSTON, F. A. BATHER, W. H. TWENHOFEL). Of the said geologists J. E. HEDE has specially endeavoured, by thorough and comprehensive field studies, to clear up the stratification and distribution of the rocks.

During the summers of 1910 and 1911 the author had the opportunity to study the rocks of Gotland and then paid special attention to their different petrographical facies. Of late years he has repeatedly returned to the island for special studies of different types of rock. During the summers of 1934 and 1937 earlier investigations were completed, especially those comprising the unstratified limestones, the reefs.

The following account will be entirely based on the author's own observations and, as to the stratigraphy, on the researches of HEDE. In some cases, however, the author has had reason to mention the observations of other geologists, and the last chapter contains a survey of different authors' interpretations of the character and formation of the reefs.

General Occurrence of the Silurian Reefs of Gotland.

The reefs of Gotland appear in different parts of the series of strata and in sediments of a somewhat varying nature. It is therefore probable that their formation and development have not been quite uniform in all cases. This is evident already from the general occurrence of the reefs, from their horizontal and vertical extension, and from their size and form.

The interpretation of the stratigraphy of Gotland has caused great difficulties, especially on account of the lithological changes of facies. Although already MURCHISON (1847) had a practically correct idea of the stratigraphy, it is nevertheless first in the last decennia that this has become strictly established, in the

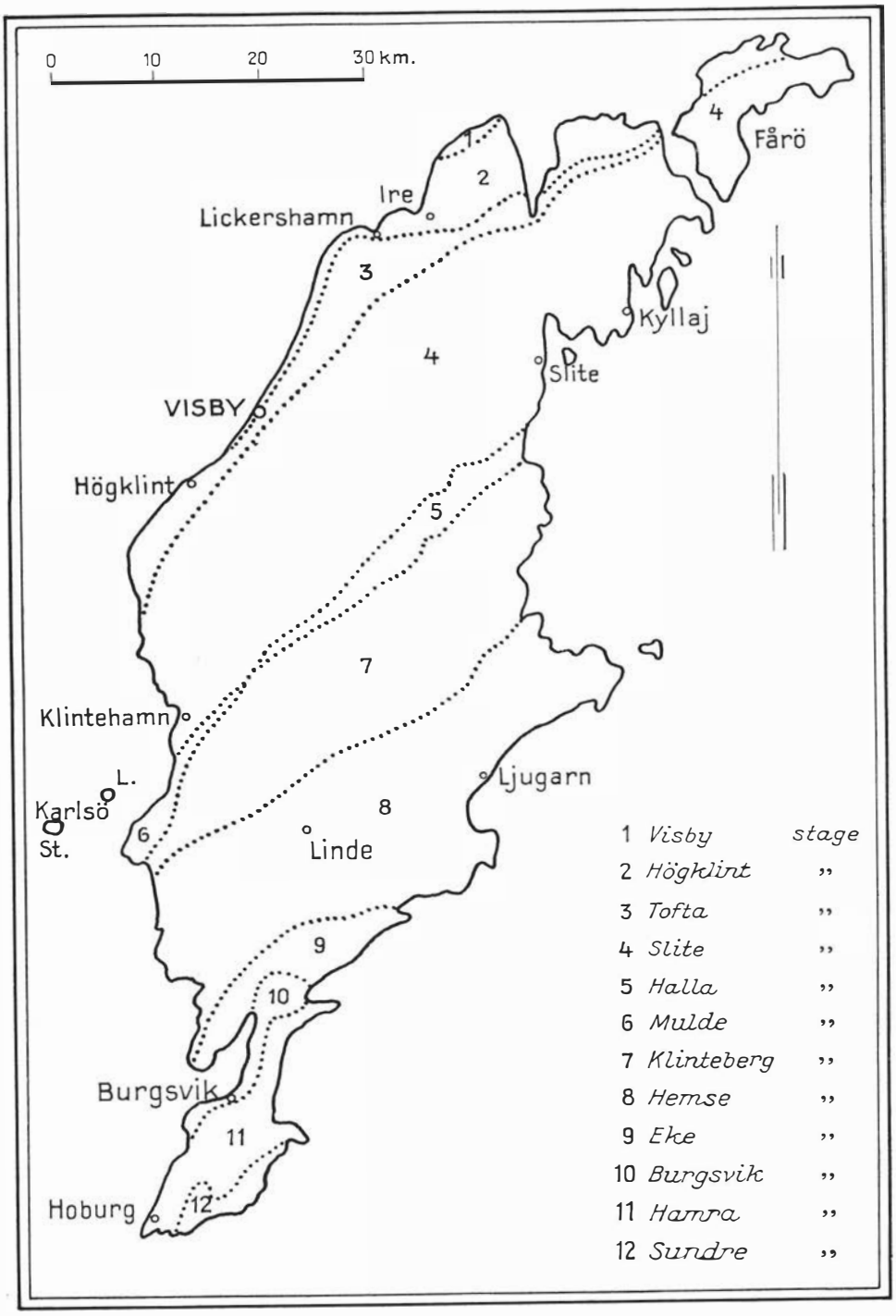


Fig. 1. Map of Gotland showing the different Silurian stages.

first place owing to the exceedingly comprehensive and thorough paleontological investigations made by J. E. Hede in connection with the revision and edition of the geological map on the scale of 1:50000.

The Silurian series of strata in Gotland, with the reefs contained in it may, according to Hede, be divided into the following parts: —

		Approximate max. thickness in m.
13.	*Sundre stage:* — crinoidal and stromatoporoidal limestones, partly developed as reef limestone	10
12.	*Hamra stage:* — marl, marly limestone, stratified crystalline limestone, and reef limestone	40
11.	*Burgsvik stage:* — sandstone, clay, marl, and oolitic limestone	50
10.	*Eke stage:* — marlstone, stratified limestone, and reef limestone	15
9.	*Hemse stage:* — marlstone, stratified limestone, and reef limestone	100
8.	*Klinteberg stage:* — stratified limestone, partly oolitic, and reef limestone	100
7.	*Mulde stage:* — marl and marly limestone	25
6.	*Halla stage:* — marl, marly limestone, fine-crystalline stratified limestone, oolitic limestone, and sporadically reef limestone	15
5.	*Slite stage:* — marl, stratified limestone, partly marly or oolitic, reef limestone, and calcareous sandstone	100
4.	*Tofta stage:* — stratified limestone, locally reef-like	10
3.	*Högklint stage:* — marl, stratified limestone, partly marly, and reef limestone	35 [1]
2.	*Upper Visby stage:* — marl and stratified marly limestone, a slight amount of reef limestone	15 [1]
1.	*Lower Visby stage:* — marl and marly limestone	10

As the stratigraphical survey shows, reef limestones are distributed almost throughout the entire series of strata of Gotland. The reefs show a particularly large development in three of the stages, viz. in the Högklint stage, in which the large reefs at Visby and on the northern shore of Gotland are situated, in the Slite stage from Fårö in NE to St. Karlsö in SW, and in the Sundre stage in southernmost Gotland. Locally very prominent reefs, however, are to be found in other stages too, specially in the Klinteberg stage (Klinteberg), in the Hemse stage (Lindeklint, Etelhem, Stånga, a. o.) and in the Hamra stage (Hoburgen).

[1] Acc. to Hede 1940.

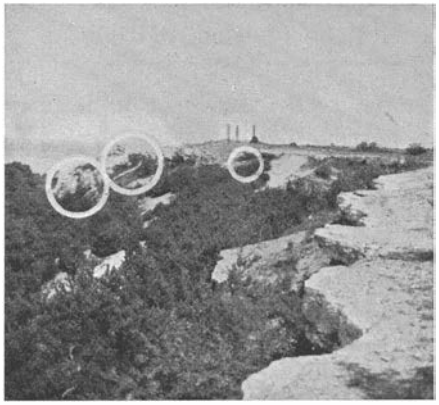
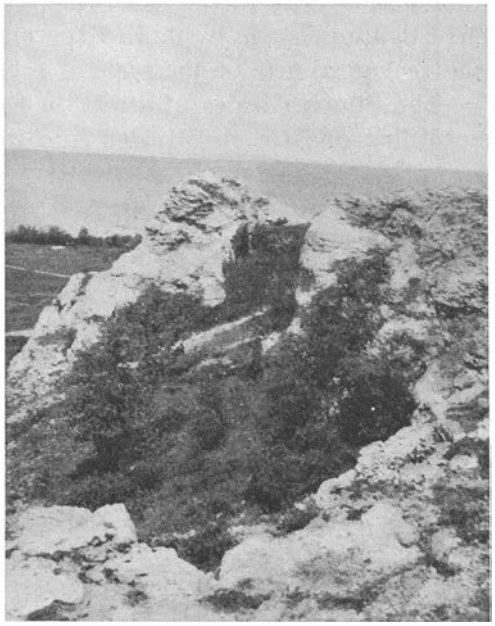


Fig. 2. The limestone cliff north of Visby. Details of the rocks are to be seen in fig. 3—5, from places marked with the three rings.



3. Upper part of the reef Galgberget, Visby.

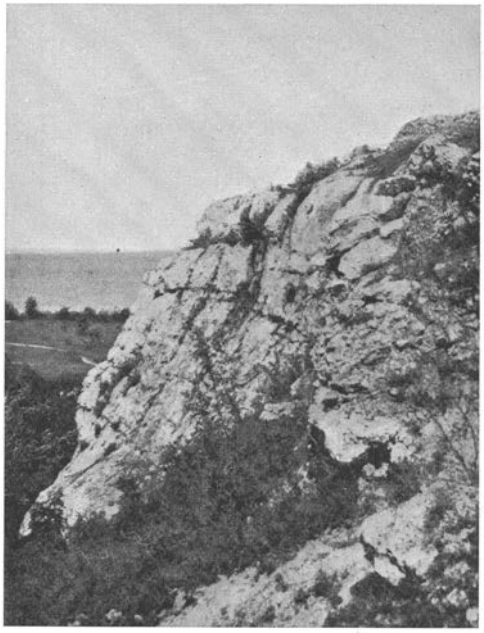


Fig. 4. Middle part of the reef Galgberget, Visby.

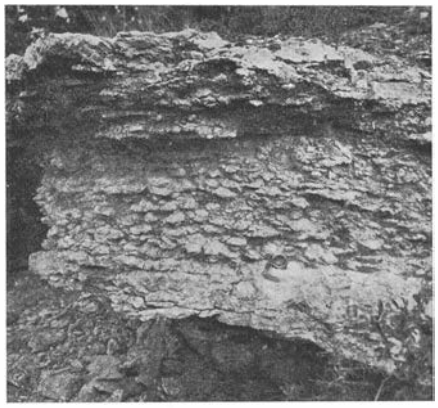


Fig. 5. Fragment limestone with stromatoporoids. Högklint stage, Galgberget, Visby. (In the small circle at fig. 2.) — $^{1}/_{12}$.



Fig. 6. Map showing the distribution of reefs in the Slite, Hemse, and Sundre stages.

Horizontal Distribution of the Reefs within a Stage.

The grouping of the reefs and their more or less frequent occurrence during a certain period of formation may of course be essentially established by a petrographical mapping down of one stage or other. I do not here intend, however, to give an account of all the reefs of the different ages or stages represented in the

series of strata of Gotland. Such an account is, I hope, to be expected from J. E. Hede in a future monograph on the Silurian of Gotland. I shall restrict myself to an attempt to show in what manner the reefs occur and to what extent they characterize the different parts of the series of strata, and then discuss their mode of formation.

The reefs are particularly well developed in and near the town of Visby and this is where they are generally first seen by visitors to Gotland. These reefs lie almost entirely in the Högklint stage and occupy an essential part of it. It has been possible to follow the reef limestone almost throughout the town (within the encircling wall) and further north and south, where it is replaced, however, by stratified limestones for longer or shorter distances (fig. 2—5). The reefs are particularly prominent north of the town in Galgberget and in Korpklint as well as south of the town in Högklint. These reefs have a relatively wide horizontal extension. In a measured section 8 km in length reef-like limestones and reefs could be observed for a distance of nearly 6 km. In the continuation of the section, however, only 1 km occupied by reef is found over the same distance. The reefs lie as a rule scattered, in the Högklint stage as well as in the other parts of the series. The reefs between the fishing-village of Ire and the bay of Lickershamn have the typical appearance of isolated unstratified limestone lumps embedded in stratified rocks.

It is evident from the above that the reefs are not uniformly distributed in a stage, a fact which is especially marked, if we turn to some of the younger reef-bearing horizons, for instance to the Slite stage or the Hemse stage (see map, fig. 6). These contain an abundance of reef limestones, also in the form of large reefs, but both stages are mainly developed as stratified limestones and marlstones.

It would of course be of great paleogeographical interest to map down the reefs of the different stages in a satisfactory manner. The difficulty of proving the presence of reef lumps covered by younger rocks hampers the cartographer and in several cases even makes the mapping impossible. Only in exceptional cases is it possible to establish the position of other reefs than those uncovered or exposed in natural or articifial sections. On the appended map,[1] however, I have tried to show the distribution of the reefs in three of the stages: the Slite, Hemse and Sundre stages. The general distribution of the reefs is no doubt correctly reproduced on this map, though only those parts of the reefs are delineated which are not wholly covered by younger Silurian sediments or Quaternary deposits.

Vertical Distribution of the Reefs within a Stage.

Only locally do the reefs show an even distribution in the different horizons of a stage. Reefs ranging nearly through a whole stage, as is frequently the case in the Högklint stage, are as a rule mostly extended in their upper part. The reef-

[1] Based on the geological maps.

building may have begun earlier at one place than at another, it may also have proceeded at one place after having come to a standstill at another. Thus the reefs have often obtained a different stratigraphical extent even in one and the same stage.

A diagram of some reefs in the Högklint and Upper Visby stages observed on the east side of the Ire bay is given here as an example of the vertical distribution of the reefs in a stage (fig. 7).

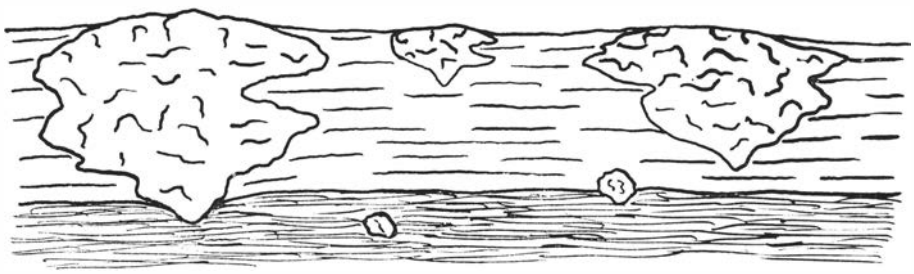


Fig. 7. The vertical distribution of some reefs in the marls of the Upper Visby stage and in the Högklint stage.

Form and Size of the Reefs.

The reefs are seldom so accessible to measurement that a quite reliable determination of their size is possible. On account of the irregularity in the form of a reef the measurements made on the exposed parts of it only admit of an approximate estimation of its volume. As a rule, however, a fairly god idea of the relative size of the reefs can be obtained, specially in cases where they are superficially situated, i. e. where they are outcropping or are covered only by thin layers of younger sediments.

As was said above, it is possible here and there to follow the reefs nearly uninterruptedly for one or more kilometers. The thickness of these large reefs is as a rule highly variable, from 1 or 2 m to 10 or 20 m.

The reef in Högklint, 6 km SW of Visby, has a maximum thickness of about 30 m, but the greater part of it is less than 6 m thick. The original extension of the reef may have been 1 $^1/_2$—2 km. In spite of the destruction of the bulk of the reef by abrasion the preserved parts show that the reef has had its greatest depth and reached its greatest height actually at Högklint (fig. 8). From this place the lower surface of the reefs rises rapidly but irregularly in all directions and at the same time the upper surface sinks slowly. In its peripheral parts the reef has locally a relatively constant thickness.

The form of the Högklint reef, showing an inverted cone with a curved and widely extended base, is often found in other reefs also. The variations are,

however, great: the top angle of the cone may be acute or obtuse, the up-turned base of the cone may be very extended, bed-like, or relatively insignificant.

In the cliffs, »klintar», situated on the western shore of North Gotland the reefs are generally of the latter type. Some of the smaller reefs on the eastern side of the Ire bay are devoid of the extent in the upper part usual in others, and the smallest ones measuring a couple of metres in diameter do not show any marked cone form either. These small reefs appear as rounded, more or less uneven limestone lumps or thick lenses embedded in stratified marl or limestone (fig. 7).

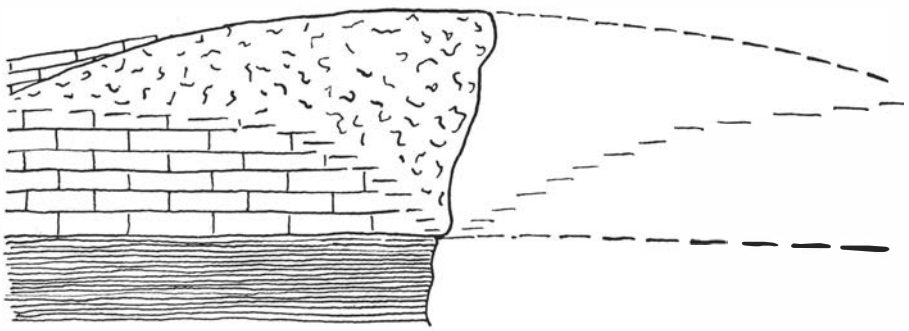


Fig. 8. Diagram of the Högklint reef by Visby and its primary extension.

In the reefs of the above-mentioned type the reef-building began in a very limited area and then proceeded outwards more or less rapidly at the same time as the reefs grew thicker (= CUMMING's *bioherm*). But in several reefs no successive growth in horizontal direction can be shown. These do not emanate from a certain point but from an extended area. In such cases the organisms that built the reef developed simultaneously within wide parts of the sea-bottom. Reefs formed in this manner have the shape of thick beds or flat lenses (= CUMMING's *biostrom*), and it is only their specific structure and fossil content that distinguish them from the surrounding stratified limestones. Among this reef-type transitions to stratified limestones is very frequent, transitional forms not to be mistaken for the genuine reefs (bioherm) which on account of reef builders with pronounced tabular development seem to be slightly stratified (see further p. 23 and 51).

Typical reefs of the above-mentioned bed-like development are present in several places, in e. g. the Slite and Hemse stages. One would also be inclined to count some of the reefs north of Visby among them. But these reefs are formed in the same manner as the Högklint reef, i. e. as conical reefs with a widely extended upper part. That they do not show any strong development in vertical direction is no doubt due to the fact that the proximal part of the reefs, »the primary cone», is not visible; the exposed parts lie entirely in the peripheral, bed-like extended portion of the reef. At Korpklint the central part of the original reef may thus have

been removed by erosion, while at Galgberget it lies a short distance from the edge of the cliff under the summit of the reef dome.

All the said reef-forms, the conical, the extensively conical, the lenticular, or the bed-like ones, are schematized. In reality these pure forms are, as pointed out above, more or less extinguished by irregularities in the reef body. The origin of the irregularities is sometimes impossible to determine, in other cases it is quite obvious. Thus it is evident that large reefs were in some cases produced by the coalescence of a number of smaller ones, the formation of which had begun at the same or a different time.

The form of the reef is very often changed by the extinction of the reef-building organisms on a part of its surface while, in other places, they continue to build up the reef. Where the growth of the reef occasionally ceases clastic material will encroach upon the reef body and form fragmental limestones enclosed in the reef or dovetailing into its sides. For the details of these irregularities, cf. the account of the relations between the reefs and their surrounding rocks (p. 53).

Building-material of the Reefs.

In the same manner as the recent coral reefs, the fossil reefs are built up partly of reef-building organisms in situ, partly of fragments of these as well as other organisms and, finally, of precipitated or recrystallized calcium carbonate. Inorganic detritus material is always added to these essential constituents of the limestone reefs. The different ingredients vary not only from reef to reef but also within the different parts of one and the same reef. Even in a relatively small reef only a few metres thick and some tens of metres in diameter there are often parts which are characterized by quite different reef-building organisms. The percentage of fragments and detritus may also be highly variable in the different parts of the reef. It is therefore always difficult to say what reef-building organisms characterize a reef that is only partly known; it is always possible that in some part of the reef portions may be found where the said organisms play a minor part and others prevail. I am fully aware of these facts now I am about to give an account of my observations on the building material of the reefs, and it is of course with the reservation conditioned by the said facts that I report on the character of some reef or other.

Primary Organic Constituents of the Reefs.

The organically formed calcium carbonate in a reef generally occupies the bulk of the reef. The frame of the reef formed primarily by sessile benthos is always more or less preserved, even if it is not possible in every special case to show in the field exactly how much or to point out in detail what parts of the reef belong to it.

Besides this frame of sessile benthonic forms preserved *in situ* the reefs contain an abundance of fragments of the same forms mixed with the remains of other sessile and a number of vagile benthogenic forms. Within and around the reefs this material builds up fragment limestones of varying thickness and extension. They are of different character owing to the nature of the material (the organic primary material) as well as to its disintegration. In places where the fragments were rounded and strongly worn by the surf a fine calcareous mud was of course also formed. Part of it was washed away from the reefs while part of it demained in the cavities and was deposited as filling between the coarser fragments. Not infrequently reef limestones are found the filling of which is mainly built up of such calcareous mud with larger fossils and fragments strewn in. Large portions are, at least apparently, devoid of proper reef-builders, a fact which gives these limestones a specific character. Several of the most beautiful rauk fields, for instance that at Lännaberget N of Slite, consist of such limestone.

On subsequent examination of the organic material in the reefs the following division is made: —

I. Reef-building organisms.
   A. Stromatoporoids.
   B. Corals.
   C. Bryozoans.
   D. Calcareous algae.

II. Non-reefbuilding organisms.

Stromatoporoids.

General Occurrence and General Development.

It may not be difficult to find portions in a Gotland reef where no stromatoporoids will be seen. On a systematic search for such portions it will, however, be observed that parts free of stromatoporoids are exceedingly small in comparison with those rich in stromatoporoids.

An examination of the reefs also shows that the different parts of them as a rule vary widely in their content of stromatoporoids. In some parts the rock may consist almost exclusively of these fossils, in other parts the stromatoporoids occur together with corals, bryozoans and calcareous algae in varying quantities. And the stromatoporoids are very often found wholly or partly surrounded by fossil fragments, calcareous and argillaceous detritus.

Already a superficial examination of the reefs shows us that the stromatoporoids occur in varying forms. Dome-shaped ones dominate in certain quarters, while more spheroidal ones entirely fill up a reef-portion in other places. The flat unevenly lenticular or wave-like curved ones are also present in the reefs, although they are more characteristic in stratified stromatoporoid limestones. (See further p. 18.)

Characteristic Features of the Rocks obtained from Stromatoporoids of different types.

It is quite natural that the stromatoporoids characterize the rock in places where they appear in abundance. In fresh fractures of the limestones the stromatoporoid sections, which are as a rule purely white, stand out very sharply, and the separate colonies of stromatoporoids are easily observed on the somewhat weathered

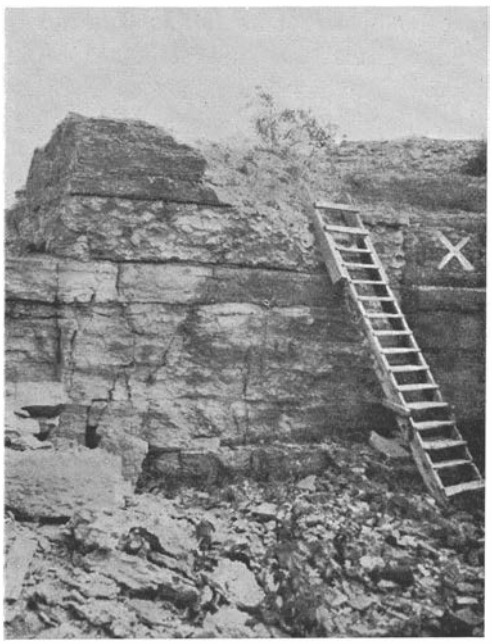


Fig. 9. Stratified limestone with stromatoporoid bed (⨯) in Tofta stage. N of Visby.



Fig. 10. Stromatoporoid limestone, bedded. Same as in fig. 9. — 1/8.

rocks and reef precipices. The rock shows quite a different structural character, if it is built up of the flat stromatoporoids, of the large dome-shaped or bun-formed ones, or of the small balls. The ingredient loose material may cause the separate stromatoporoids to stand out more distinctly; the character they impart to the reefs is thus still more striking. The purer the stromatoporoid stock and the more isometrically developed the separate calcareous lumps are, the stronger is the impression of a massive rock. The other extreme is found in reefs or reef portions rich in loose material of varying coarseness or in reefs with flat stromatoporoids (and perhaps also similarly constructed corals). In these rocks thin lenses of loose marl are very frequent. The structure in these reefs is never clearly massive. The parallel structure is often distinct, sometimes bed-like, even if real, extended beds are wholly absent. The transition between these reefs and the surrounding bedded

limestone may be fairly imperceptible, specially if the bedded limestone as well as the reef has a high percentage of stromatoporoids.

It should be emphasized in this connection that a higher or lower percentage of stromatoporoids in a rock does not decide its reef character. A bedded limestone may consist almost exclusively of these calcareous bodies. Examples of this are found in many places in Gotland (fig. 9—10). On the other hand a reef is, as said above, to no small extent constructed from fragments, loose fossils and detritus, and besides that corals and other reef builders may almost completely displace the stromatoporoids locally. It would therefore be incorrect as far as Gotland is concerned to put a sign of equality between reef limestone and stromatoporoid limestone, as it would also be quite inaccurate to call these limestones coral reefs.

It is nevertheless undeniable that the stromatoporoids play a much more important part in the reefs of Gotland than corals and other fossils. The question now presents itself. How large a part of the reef body do they on an average occupy? A direct estimate is impossible on account of the changes and the unsatisfactory exposures in a reef, and an estimate can never claim to be accurate in a very high degree. In certain reefs (or in their main part) the content of stromatoporoids may exceed 70 per cent of the entire body but as a rule it may not be above 50 per cent. In this estimate I have made special allowance for the loose material that forms a very important ingredient in all reefs.

Special Development of the Stromatoporoids.

For the comprehension of the manner in which the stromatoporoids build up the reefs a study of their growth as well as the structure and other qualities is inevitable.

It is often possible to find the origin of a separate colony of stromatoporoids. Sometimes one can even detach the calcareous body from its substratum and then (at best) see how it has grown out of a centre, or a number of centres (fig. 11—12). This is best visible where the substratum has consisted of clay or marl. As a rule the reef-building stromatoporoids had a more solid substratum of shell fragments, bryozoan colonies, or older stromatoporoids and it is then more difficult to separate the stromatoporoidal lump from its fastening. The calcareous body had become attached to the substratum in such a manner that an attempt to disengage it is seldom successful; the rock will sooner break to pieces along growth layers in the stromatoporoid than in the boundary face towards its solid substratum.

If a stromatoporoid colony developed on a solid substratum, it could resist even the strongest waves and breakers. It is remarkable that wherever we find in the reefs detached stromatoporoid stocks that have been exposed to wave activity, the rock contains an abundance of calcareous fragments and marly, often distinctly stratified parts. In these cases the stromatoporoids did not grow on a solid ground. The loose substratum was disrupted with them by the waves. In

several coarse reef conglomerates the result may be seen and the forming process reconstructed accordingly.

The more extended in form a stromatoporoid colony was already from the beginning of its existence, the better could it bind a loose substratum. Even clayey mud or calcareous sand formed from fossil fragments composed a good ground for such bed-like stromatoporoids. They spread as covers over larger or smaller surfaces, and if their growth was not checked by abundant mud deposits, they formed a solid basis for other reef builders.



Fig. 11. Section through the lower part of a stromatoporoid bed showing the centra of growth. Högklint stage. Storugns. -- 1/1.

It may be asked, if the different shape of the stromatoporoids (spheroidal, dome-shaped, tabular, etc.) is due to different developmental conditions or to differences of species. The Swedish stromatoporoids have never been subjected to a detailed examination, and on that account we do not know to what extent they represent more or less numerous distinct species and genera. The constant specificity found in several of those forming the bulk of the reefs makes it more than probable that definite qualities of species are a condition of this. However tempting it might be to subject the matter to a more detailed investigation, I must desist from it.

Without entering into an analysis of the stromatoporoid material from a systematical point of view I shall give some information about the different shape-types or type-groups. For the general character and structure of a reef the dominant forms of stromatoporoids play a decisive part.

As to the development on a large scale the following types, as was mentioned above, may be distinguished among the stromatoporoids in the reefs of Gotland: — the spheroidal, the dome-shaped or nodular, the tabular, and the columnar ones.

The *spheroidal stromatoporoids* vary in diameter from a couple of centimetres to over one decimetre. Pure stocks of the smallest type with the separate lime bodies from walnut- to tennisball-size are rarely met with, while the fist-sized mixed with larger and smaller ones are more common.

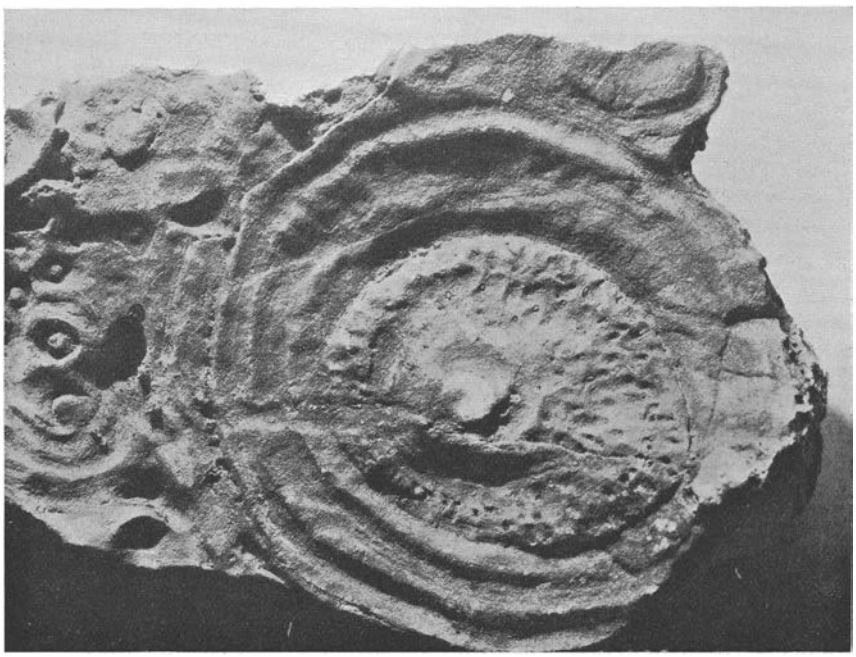


Fig. 12. Base plan of a stromatoporoid. To the left imprints of cup corals. — Hemse stage. Etelhem. (Pl. 1037). — $^1/_1$.

The spheroidal stromatoporoids are generally compact without distinct laminae. Already macroscopically they differ in structure from *Sphaerocodium*, *Spongiostroma* and other calcareous algal balls. Under the microscope they show the same structural type as other stromatoporoids. In most cases, however, the strong recrystallization in the calcareous mass has extinguished the primary structural features. For that reason I have not been able to follow the process of growth in each separate lime body. Nor does the external shape, which may differ considerably from the spherical, give us, as far as I can see, any reliable guidance for the estimation of the part these stromatoporoids played in the construction of the reef. Judging from their occurrence in large quantities, they were firmly attached to their substratum and thus formed a solid reef column.

Reefs built up of spheroidal stromatoporoids are conglomeratic or brecciated in structure (fig. 13 and 41—42). As a rule the outlines of the stromatoporoids are not very distinct on an exposed reef surface, owing to the fact that matrix and cementing material consist to a large extent of almost as pure a calcium carbonate as the stromatoporoids. Secondary fissures and infiltrations make it difficult to form an immediate opinion about the construction of the reef. By strong brecciation

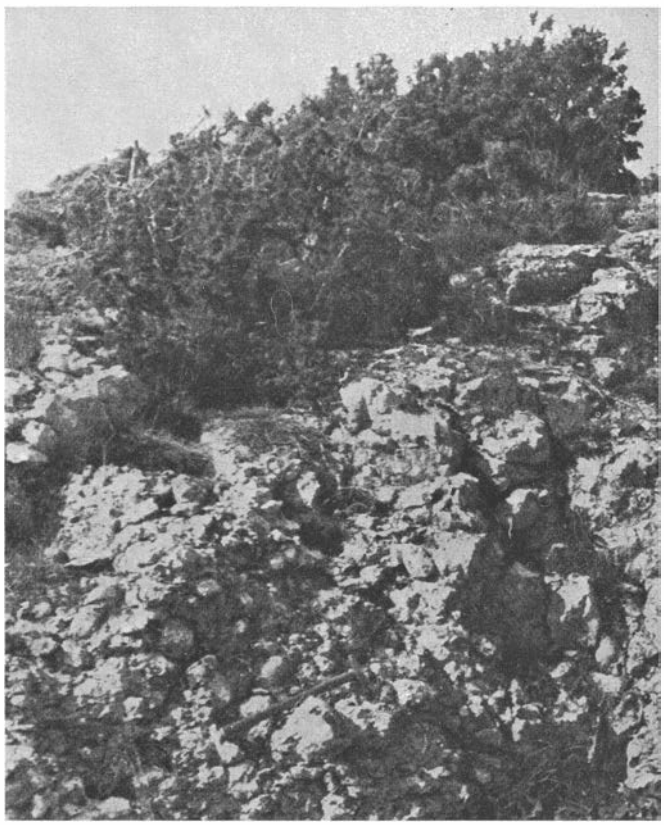


Fig. 13. Stromatopora reef. Structure comglomeratic. Högklint stage. Högklint, S part. — About 1/20.

other reefs, e. g. with large stromatoporoids, may obtain the same general structural character as those discussed here.

Under the term *dome-shaped or nodular stromatoporoids* I comprise all the rather varying types which differ from the tabular ones by their very arched shape and from the spheroidal ones by their greater breadth. Dome-shape in the proper meaning of the word, i. e. a more or less hemispherical form with a plane base is not rarely seen in marly rocks. The relatively freely developed ones occurring

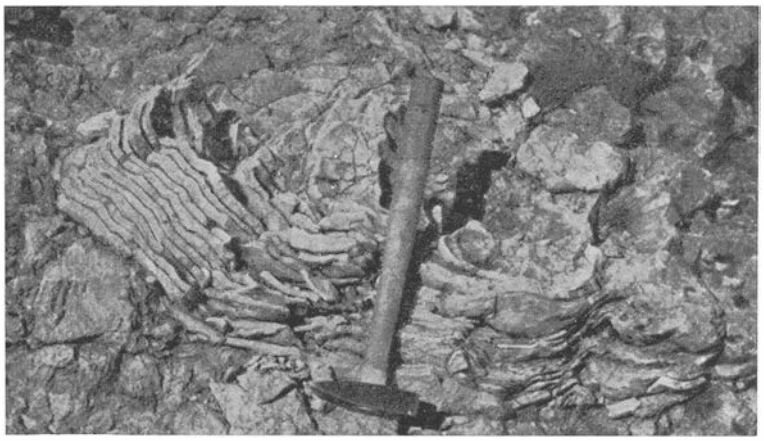


Fig. 14. Large stromatoporoid splitting up in thin laminae of growth. Högklint stage. Fårön. (Film 10, 20/1937.) — 1/9.



Fig. 15. Reef limestone with large nodular stromatoporoids. Linde klint.

solitary in fragment limestones are often shaped like thick lenses (fig. 15 and 42). In the reefs we find a more irregular shape, much the same as we see in strongly rounded but nevertheless uneven limestone blocks. A pronounced extension in a certain direction is not uncommon.

These stromatoporoids have grown radially from an eccentric point in the

fully developed lime body. In cases with a relatively plane base, which was formed when the substratum consisted of loose clayey material, concentric rings of growth and in them sometimes distinct moulds of overgrown solid objects are visible in the lime body (fig. 11—12).

The above-mentioned stromatoporoids are generally larger than the spheroidal ones. Not infrequently they measure $^1/_2$—1 m in length. They often show a distinctly lamellar structure (fig. 14).

The large nodular stromatoporoids may occur in such great numbers that they form the bulk in certain parts of a reef. The rock appears as a coarse conglomerate, especially on weathering and disintegration (fig. 15). Reefs with the large nodular

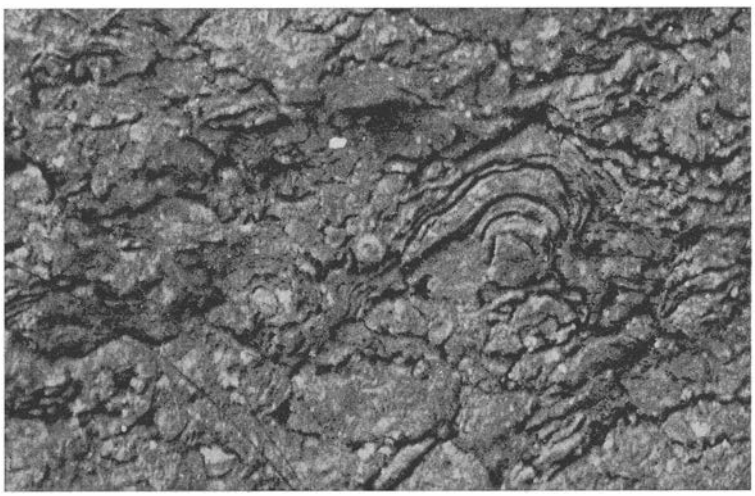


Fig. 16. Beds of dome-shaped stromatoporoids. Högklint.

stromatoporoids may contain an abundance of other stromatoporoids as well as corals and crinoids.

If several dome-shaped stromatoporoids developed side by side, they grew together into a cover with dome-shaped elevations (fig. 16). This type is fairly common in Gotland, both in reefs and stratified stromatoporoid rocks. In development it occupies an intermediate position between the dome-shaped and tabular ones. In the same manner as the former, but contrary to the latter, these stromatoporoids show pronounced laminae.

The *tabular stromatoporoids* developed as covers or thin lenses on the sea bottom. Their shape is best seen in the stratified stromatoporoid rocks which here and there surround the reefs (see fig. 17). The separate stromatoporoids are mostly isolated from each other by thin marl beds. The upper as well as the lower surface

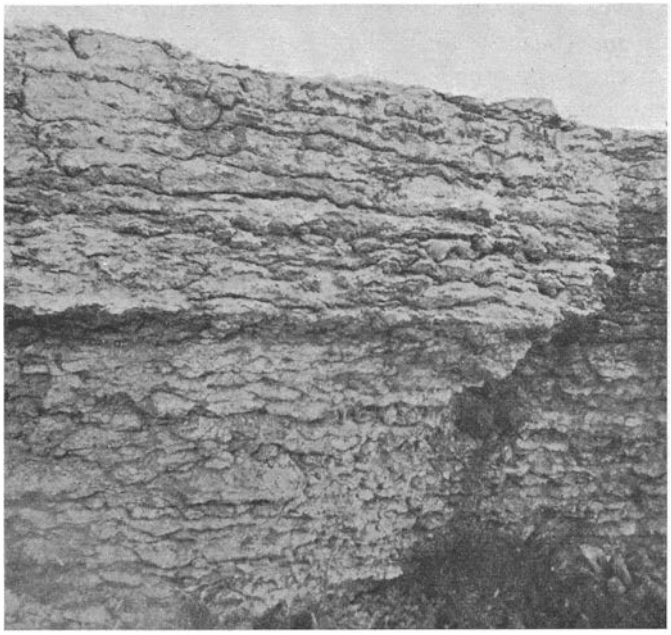


Fig. 17. Tabular stromatoporoids in stratified limestone. Galgberget. Visby.

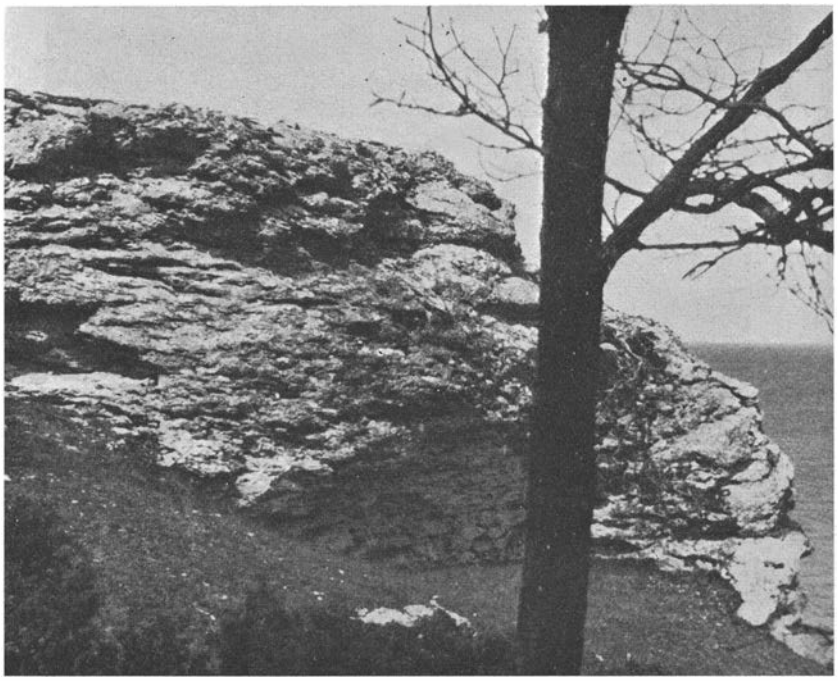


Fig. 18. Reef limestone with tabular stromatoporoids. Lickershamn.

is curved, and each separate cover or bed has a thickness that varies in detail but is on the whole constant.

In the reefs these stromatoporoids do not show the same regular development, although they are also there widely spread in the horizontal plane or, more correctly, parallel to the sea-bottom. Their thickness and form was varied by irregularities in the substrata and a locally varying rate of growth. Here and there deposition of clayey detritus temporarily impeded the growth in a vertical direction but before long the stromatoporoids again spread over the reef. Stromatoporoid limestone formed in this manner may show a characteristic aspect (fig. 18) reminding of an

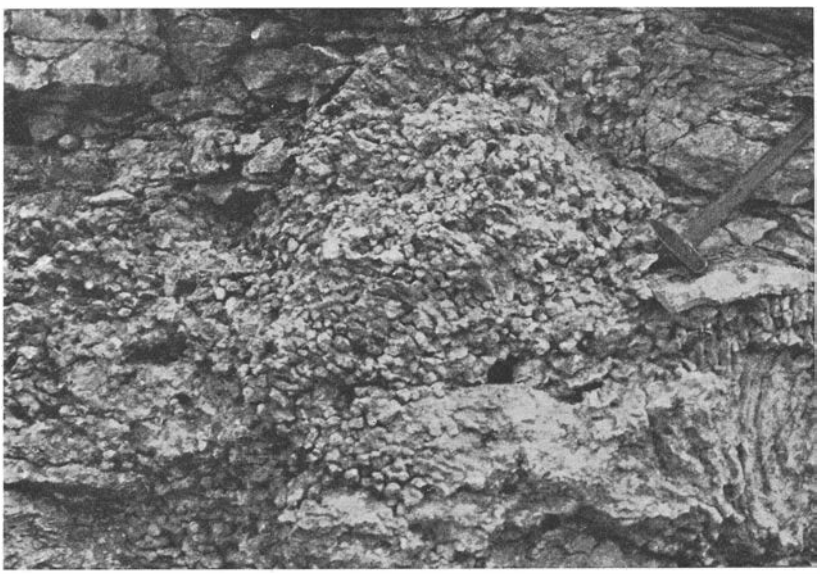


Fig. 19. Columnar stromatoporoids. Korpklint, Visby.

uneven stratification. In spite of this structure, however, the rock is practically a compact reef (cf. p. 52, fig. 45—46). The embedded lenses of detritus cooperate with the tabular stromatoporoids in creating the parallel structure but they do not suffice to divide the limestone into separate beds.

Stromatoporoids of the above-mentioned horizontally spread, irregularly tabular type are as a rule devoid of the distinctly lamellar structure characteristic of many dome-shaped or nodular stromatoporoids. The microstructure, however, is similar in all forms, but in the tabular as well as in other types it was generally deleted during the recrystallization.

In Gotland stromatoporoids of the last-mentioned type may be found also in normally bedded limestones. They may form a relatively compact mass with insignificant amounts of embedded detritus and fossil fragments. The regular tabular or flat lenticular development so very common in the stromatoporoids of

more marly beds is not always found in pure limestones. The separate stromatoporoids are irregular in outline (fig. 10, p. 17). They are sometimes only sporadically present sometimes they fill up a whole bed. In the latter case a sudden growth was after a time followed by a complete extinction.

Columnar stromatoporoids are found here and there in the reefs. They play the same part as branched corals and bryozoans, i. e. they are more to be considered as mud-traps than as reef builders in a restricted sense. As far as I can find they occur only sporadically. On a closer investigation of the branched or columnar calcareous organisms of the reefs it is found that the fine-branched ones generally consist of bryozoans and the coarser ones of corals and to a less extent of columnar stromatoporoids (fig. 19).

Preservation and Structure of the Stromatoporoids.

Common to all the stromatoporoids in the Silurian of Gotland are the purity of the lime body and its tendency to recrystallization. The characteristic organic microstructure may often be traced (fig. 20—21) but the finer details are as a rule deleted. This holds also true of the details in the sculpture of the surface. The macroscopic features, on the contrary, are distinctly visible especially where the stromatoporoids occur in marly reefs or are embedded in fragment masses, in calcareous algae, bryozoans, or other fossils which contrast with the stromatoporoids in colour, shape, or structure.

As was pointed out above, a lamellar structure is very distinct in many stromatoporoids, and on weathering the body may break into thin curved laminae. Sometimes these are separated by a thin argillaceous membrane, but often no foreign embedding is visible.

The lamellar structure may also be observed in certain corals, for instance in bun-shaped *Heliolitidae* (fig. 26 p. 33). It is remarkable that the latter show this structure most distinctly in just those localities where the lamellar stromatoporoids are best developed. Strong variations in growth, particularly breaks in it, may be the origin of the lamellar structure. This may therefore rather be regarded as an environmental phenomenon than as a character of species.

Environmental Character of the Stromatoporoids.

As said above, the stromatoporoids never form a reef by themselves, they always occur together with other reef builders and lime-producing organisms of different kinds.

In the following chapter I shall give an account of their occurrence, and I only want to premise here that the quantity of foreign material varies widely in the

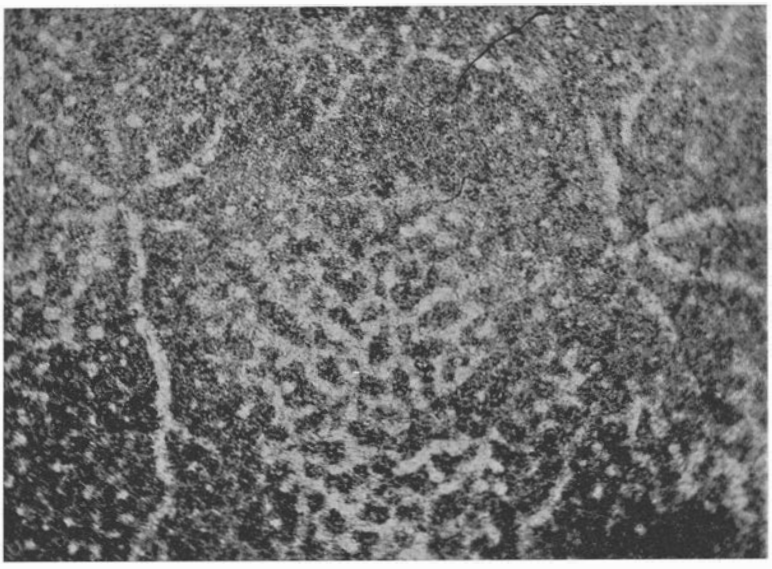


Fig. 20. Stromatoporoid—tangential section. Hammarshaga hällar. (Pr. 5386, pl. 1039). — 20 ×.

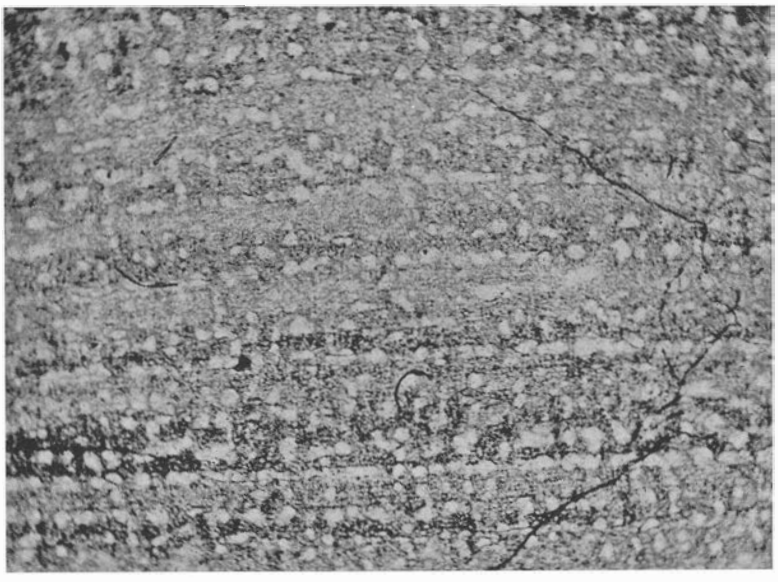


Fig. 21. Stromatoporoid—radial section. Hammarshaga hällar. (Pr. 5387, pl. 1040). — 20 ×.

stromatoporoid limestones. In some portions of reefs it may first and foremost consist of calcareous algae, in others of corals or bryozoans. The organisms built up the reef side by side in the same manner as they do it in recent reefs.

The proportion of loose fossils and fossil fragments is highly variable. Crinoidal fragments and fine calcareous ooze with small remains of fossils are most abundant. Detritus, usually a greyish green argillaceous matter, fills up several small cavities and appears also as a thin coating on the stromatoporoids.

The stromatoporoids are not so well known oecologically that they can be used as environmental indicators for the present. From what is said here of the associated organisms and the nature of the rock the conclusion may, however, be drawn that the stromatoporoid reefs were formed in the sea at places where the water was in free motion (large amounts of worn fragments), relatively pure (low percentage of detritus), and relatively shallow (algae in situ). The absence of algae in certain stromatoporoid limestones indicates that they were formed in deeper waters.

Corals.

In the reefs of Gotland an abundance of corals are found, *Tetracoralla* as well as *Heliolitidae* and *Tabulata*. Their development varies, and the importance of the diverse forms as reef builders differs greatly. Simple corals, cup corals, may be found in the reefs but they do not play any part whatever there. The muddy bottom-bed is their proper environment (Hadding 1933, 36). There are, however, many real reef builders among the composite tetracorals as well as among *Heliolitidae* and *Tabulata*.

General Occurrence and General Development.

The corals occur in the reefs partly as branched stocks, partly as compact masses, very often as horizontally extended bodies varying in diameter and thickness.

The branched corals are sometimes tetracorals (e. g. certain *Cyathophyllidae*), sometimes tabulata corals (e. g. *Pachypora*). They do not belong to the prominent components of the reefs, but here and there large colonies are apt to spread in the midst of other reef builders (fig. 22). The connected reef portions, however, in which the branched corals form the solid skeleton, rarely occupy more than a few cubic metres.

The branched corals developed particularly in the parts of a reef most protected against the waves, e. g. in depression between portions built up of stromatoporoids and »massive» corals. On account of this mode of occurrence the branched corals were embedded in calcareous fragments and fine mud. When these corals occur on the border between reefs and marlstones or in reefs abundant in detritus they are, like the more finely branched bryozoans, surrounded by clay or marl. The *Halysites* stocks were also good mud traps (cf. Hadding 1933, 43).

The *unbranched, massive coral stocks* are sometimes bun-shaped, sometimes tabular. As a rule the shape changes with the character of species, but sometimes

the environmental conditions also seem to have influenced the formation as well as the more or less rapid growth.

In the lower parts of a Gotland reef an abundance of *Tabulata* are often found and not infrequently they form a substratum for other reef builders. Colonies of *Halysites* as well as widely spread forms of *Favosites*, *Propora*, etc. offered a relatively good foothold, even if they themselves rest on marly layers or other loose material. Together with stromatoporoids and calcareous algae they make a reef-building solid already in its primary part. These and other mud-resistant corals

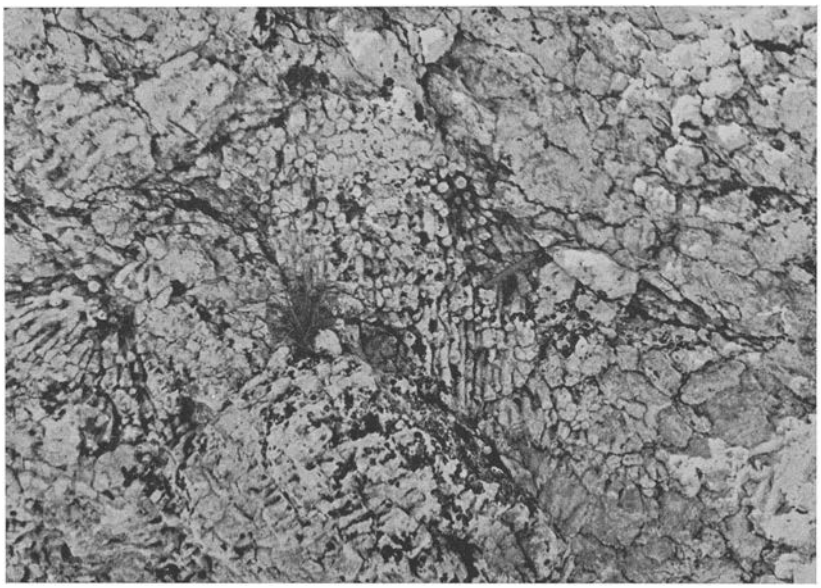


Fig. 22. Reef limestone with coral stocks. St. Karlsö. — 1/10.

also occur in the interior of the reef proper, though always together with other forms, especially representatives of the genera *Acervularia, Stauria, Thecia, Heliolites*, etc. As more occasional observations of these corals seem to have resulted in a somewhat mistaken opinion of their importance as reef builders I shall enter more fully into this question.

Wiman (1933) has called attention to the stratified structure that may be traced in the reefs of Stora Karlsö. In a schematized drawing (p. 281) he presents a picture of it, such as it appears in one of the cliffs. As an explanation of the structural form Wiman declares that the limestone is to a large extent built up of a tabularly developed coral, *Thecia swindernana* (Goldf.). This, then, would be an example of a coral occurring in such an abundance as definitely to characterize a Silurian reef. As the case is of great interest I have made a special journey to Stora Karlsö in order to study it. Just as on an earlier occasion when I did not observe the

dominant part of the *Thecia* laminae, I made thorough investigations in the precipices as well as on the surface of the reef this time also.

My investigations did not give the same result as WIMAN's. Certainly, I found a lot of *Thecia*, but not in such quantities that they characterized the reef. They do not occur in such numbers that they should be denoted as particularly important reef builders worth mentioning above other corals.

As far as I am aware -– and I do not base my opinion on studies in the field only but also on a thorough investigation of samples collected — the reefs of Stora



Fig. 23. Stratified fragment limestone. Slite stage. Austarberget, St. Karlsö.

Karlsö are built up essentially in the same manner as other Gotland reefs of corresponding type. The stromatoporoids form the bulk of the reef-building organisms. Their form is as a rule tabular, about the same as in *Thecia* and several other corals. The reef-structure is similar to that found in other places where stromatoporoids of this type dominate (cf. p. 51, fig. 45). The term Thecia-reef is misleading and the term coral reef is inopposite (see further the review of WIMAN's paper, p. 86).

It should be emphasized that the reef limestone of Stora Karlsö grades into normally bedded fragment limestone (fig. 23), and that this transition is so imperceptible that it is difficult or impossible at a distance to determine where the reef ends and the beds begin.

Tabular corals are not specially characteristic of the reefs of Stora Karlsö. They are found in great numbers in several other quarters, especially together

with the tabularly developed stromatoporoids. This is for instance the case in the bed-like developed parts of the reef at Linde klint (the Hemse stage), where I have observed centimetre-thick laminae of *Stauria* dominating parts of the reef. Also here, however, the stromatoporoids play an important part and, as was shown above, they have in some parts passed from tabular shape into irregular bun-shape. The Linde klint reef is rich in fossil fragments and it only forms an unimportant part of the Linde klint, which consists essentially of stratified limestones. In these also an abundance of tabularly developed corals occurs.

Just as portions built up to an essential extent of branched corals may be found in a vertical section through a reef, so fairly large areas (several square metres) covered by some tabularly developed coral may be observed in the present or previous upper surface of a reef. A closer scrutiny of the reef, however, always shows that the corals occur as a dominant factor only in limited parts of the reefs. The tabular and bun-shaped corals resisted the disintegrating power of the waves and tidal currents better than the branched ones. Everything goes to show that they were generally preserved in their place of growth. A stock-taking of the fossil content in a reef will therefore distinctly show to what extent corals of this type contributed to the building of the reef.

The author has taken stock of several reefs in different parts of the series of strata and found that, irrespective of the above-mentioned local enrichments, the corals occur only as an important ingredient in the reef body.

It was pointed out above that the corals play a secondary part in comparison with the stromatoporoids. It is often found that calcareous algae and bryozoans also contributed to the reef body in a higher degree than the corals. These nevertheless merit special attention. They impart to the reefs a greater variation and a more interesting composition than they would otherwise have. The great variations in shape and size shown by the corals themselves contribute in a high degree to this.

Mode of Preservation of the Corals.

The external habit of the corals is generally so well preserved that they are immediately recognizable. Their microstructure may have been lost on the recrystallization, but as a rule it is quite distinct (fig. 24—25). The corals had primarily also a more marked structure than the stromatoporoids, and in the more or less altered Silurian reefs this difference is still more striking.

When the corals developed on the reef they were firmly rooted to their substratum: another coral, a stromatoporoid, or an algal limestone. Sometimes they spread, following the irregularities of the substratum, sometimes they grew upwards

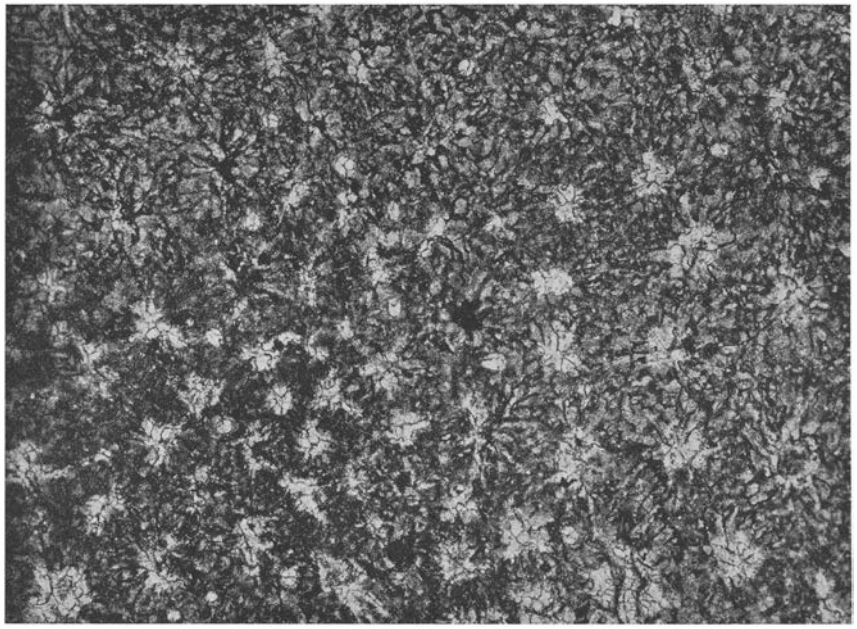


Fig. 24. *Thecia swindernana* (GOLDF.) Tangential section. Gotland. (Pr. 3594, pl. 1067). — 17 ×.



Fig. 25. *Thecia swindernana* (GOLDF.) Longitudinal section. Gotland. (Pr. 5393, pl. 1063). — 17 ×.

or radially outwards from the starting-point. Sometimes they show distinct laminae of growth along which they disintegrate (fig. 26). This refers of course specially to the bun-shaped and tabular ones.

Environmental Character of the Corals.

The occurrence of the corals together with other reef builders shows a certain regularity that may lead to conclusions concerning symbiosis or demands for a certain special milieu. Remarkable is also the general occurrence of branched



Fig. 26. Dome-shaped, shaly coral (*Heliolites*) in reef limestone. Digerhuvud, Fårön.

corals in to all appearances still (mud-catching) portions of the reefs. The compact coral lumps developed together with the stromatoporoids also where the reef was most exposed to destructing agents.

In the reefs intermingled tabular corals and stromatoporoids may be found grown together into apparently homogeneous bodies. If a distinct structure or other certain characteristic features of e. g. a coral are observed at an occasional point only, one is apt to estimate the whole body from this observation. In the account of the diagenesis of the reefs this matter will be further illustrated.

The corals sometimes occur together with calcareous algae in a manner worthy of notice, even if it cannot be said to be particularly characteristic. In fig. 33—35 such an interesting occurrence is reproduced (see also p. 40).

This algal and coral limestone grades in horizontal direction into stromatoporoid limestone with large flat stromatoporoids. The reef of which they form part has no great extent but is included as a local formation of an otherwise stratified limestone within the Högklint stage.

Bryozoans.[1]

One may hesitate to count the bryozoans among the reef builders proper. Only the branched forms occur in such large numbers as to be of importance as rock builders, but on the other hand their fine branches are not suited to be one of the building elements in a reef as they cannot carry the weight of other reef-building calcareous organisms. As a rule the branches of the bryozoans break and form part of the fragment material that fills the interstices in the reef or spreads in its environments.

Here and there in the reefs, however, undamaged colonies of bryozoans are found. Through favourable circumstances they were preserved in their original shape and milieu of formation, and like the branched corals they form part of the reef-building itself.

The bryozoans did not develop in breaker zones, of course, but in the best protected parts of the reef. The clustered fine branches prevented the mud settling around them from being washed up again, and clayey detritus, calcareous mud and fossil fragments accumulated gradually around the colony of bryozoans (fig. 27—28). Had this been entirely buried in such a fine material before it was broken by waves or slides, it might also have been preserved. It might even have served as a substratum for other reef builders.

Bryozoans are sometimes observed in a relatively intact state overgrown by stromatoporoids. In such cases too the branches are enclosed in argillaceous and calcareous mud. In the pure, white masses of stromatoporoids these parts are conspicuous as foreign elements. These bryozoans are often particularly well preserved and it is frequently possible to isolate large colonies.

The bryozoans vary in type, though the majority are *Coenites* forms. Their branches are sometimes finer, sometimes coarser, generally 2—3 mm in diameter. In the stratified sediments occurring in the neigbourhood of the reefs we find the same forms as in the reefs.

Calcareous Algae.

It is difficult to determine the contribution of the calcareous algae to the building of the reefs of Gotland. One is apt to overlook the majority of them. The reefs are devoid of such well-known and often very conspicuous algal forms as the balls of *Spongiostroma, Sphaerocodium* or *Girvanella*, at any rate in their typical development, even though they are very abundant in the stratified sediments of the over- and underlying beds. The same holds good of the *Siphoneae*, the fine tubes of which are mostly found in marlstones. Algae of the *Solenopora* type, on the contrary, are a characteristic ingredient in several reefs (fig. 29), and having

[1] As in his older papers the author counts the *Coenites* forms among the bryozoans.

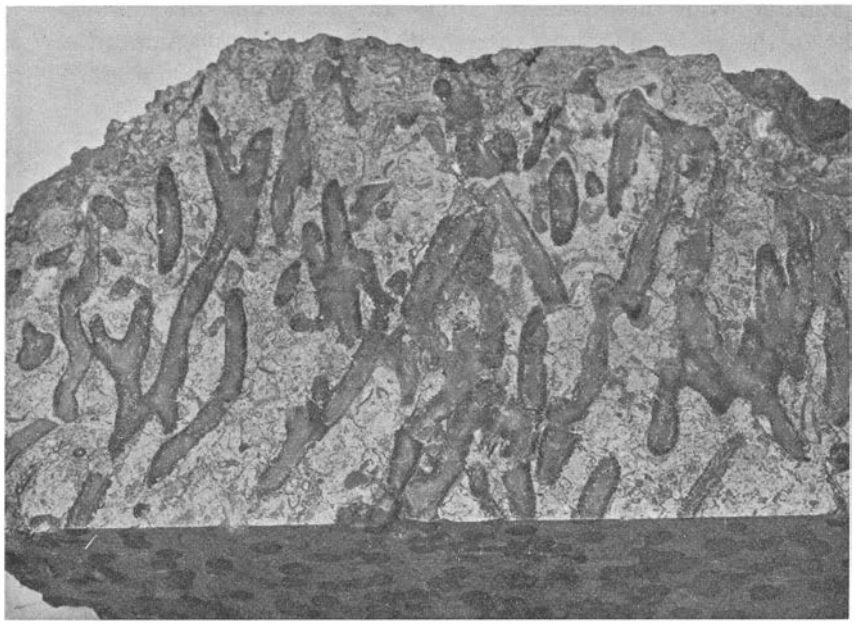


Fig. 27. Bryozoans in calcareous matrix. Reef E of Ire bay. (Pl. 1036). — 1/1.

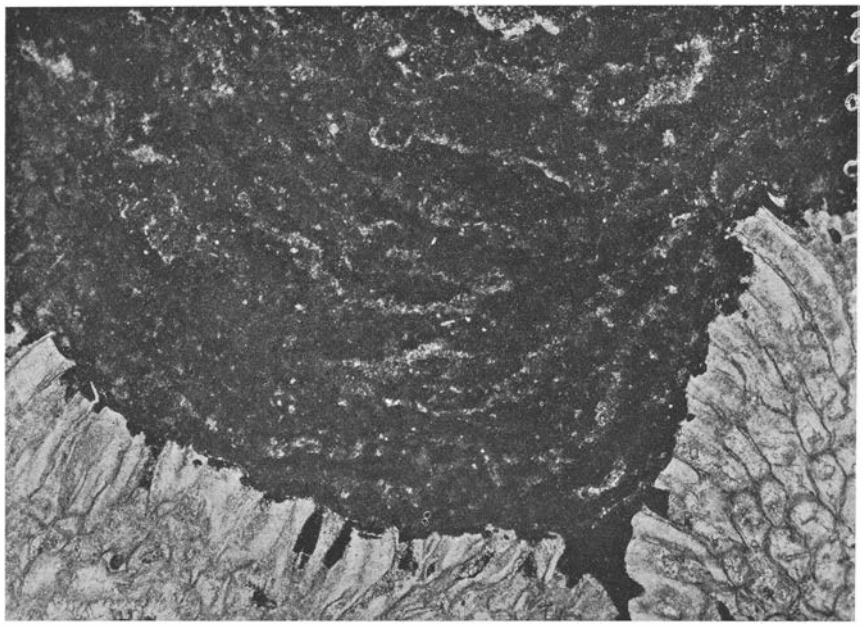


Fig. 28. Muddy matrix around a colony of bryozoans. Reef limestone of Slite stage. St. Vede. (Pr. 3263, pl. 1068). — 17 ×.

become familiar with their peculiar appearance one will find that they are more abundant in the reefs than was suspected. Of still greater importance, however, are the covers or crusts formed by types with Sphaerocodium structure (*Pilothrix*), although these are more seldom macroscopically identifiable.

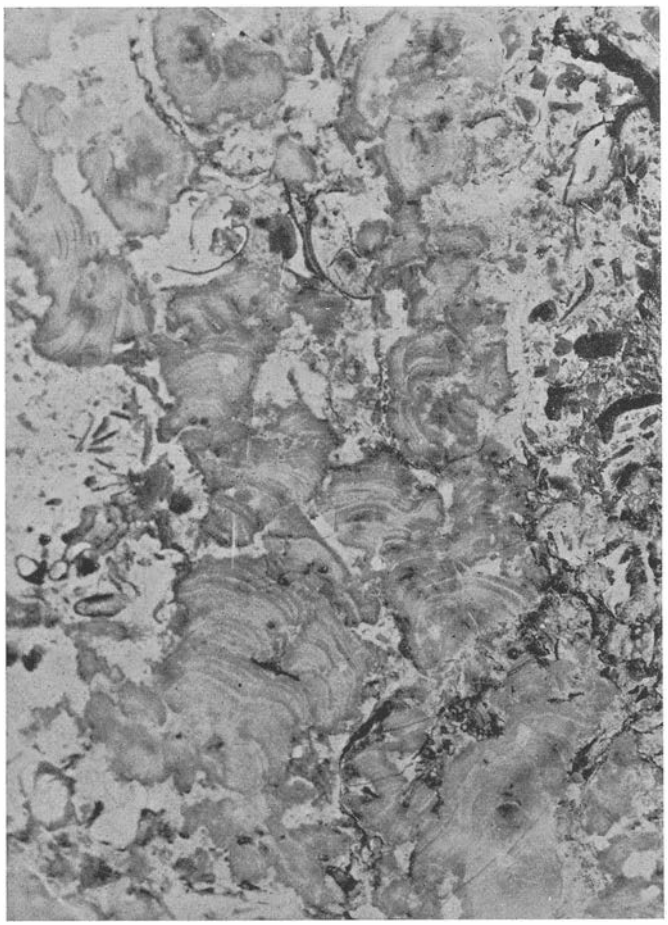


Fig. 29. *Solenopora* in reef limestone. Visby. (Pl. 952). — 3 ×.

The calcareous algae never appear in such large quantities in the reefs of Gotland as to give them a definite character. Their importance for the reef-building proper is that they keep scattered loose fragments together, creating a substratum for other organisms. Their formation of limestone was a result of the cooperation (or struggle) with stromatoporoids, corals and bryozoans which, according to the evidence of the rocks, they had engaged in. In the following I shall throw some more light on these circumstances, but first say a few words on the occurrence of the *Solenopora* forms.

Solenopora.

Three species of *Solenopora* occur in Gotland (ROTHPLETZ 1913), both with a generally well preserved microstructure that makes a reliable identification possible (fig. 30).[1] They are easily recognized macroscopically also by their compact, almost china-like mass. Their shape varies and is as a rule very irregular. The



Fig. 30. *Solenopora* and *Pilothrix* in reef limestone. Ire. (Pr. 5355, pl. 1048). — 17 ×.

calcareous body grows from the point of attachment radially outwards and upwards with greater and greater deviations during the continued growth. It is divided into a number of different, very irregular lobes (fig. 29). The interstice between them is filled by calcareous mud and fragments.

The *Solenopora* forms show distinct concentric laminae of growth. These are thin, as a rule less than 1 mm thick, and appear only as a fine pattern visible in cross-sections of the calcareous body.

[1] On the species *Hedströmia* akin to *Solenopora* see ROTHPLETZ 1913.

In the reefs *Solenopora* do not occur in symbiosis with other algae or with stromatoporoids or in any clearly definiable environment. These algae are found in the reefs as well as in the bedded fragment limestones; in the former together with stromatoporoids, corals or bryozoans and in the bedded limestones also together with *Spongiostroma* and *Sphaerocodium*. *Solenopora* was of course, like other algae, confined to parts of the sea-bottom within reach of the sunlight.

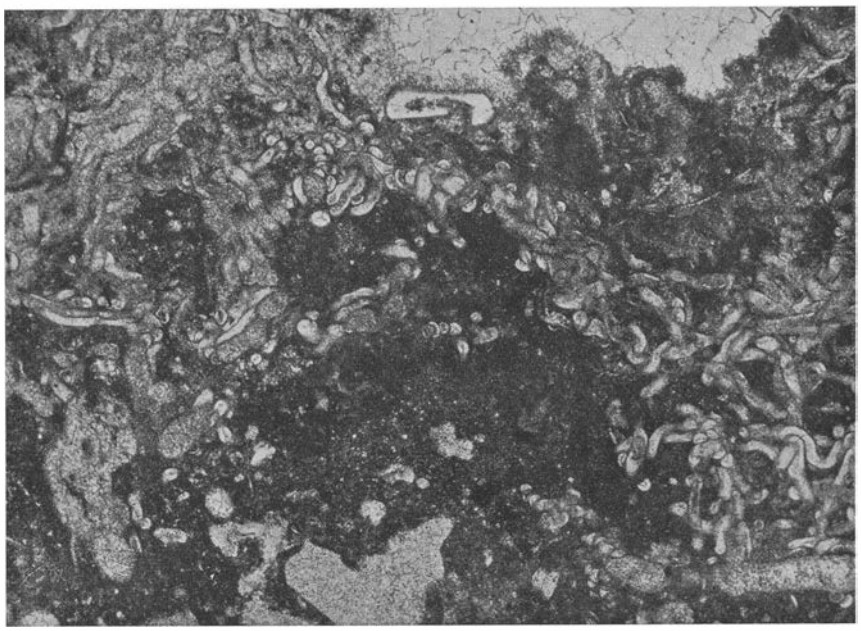


Fig. 31. Felty layer of calcareous algae in reef limestone. Klinteberg. (Pr. 3317, pl. 1054). — 17 ×.

Pilothrix.[1]

When speaking of *Pilothrix* I refer to an algal limestone of the same structure as the well-known one from the balls of *Sphaerocodium*. ROTHPLETZ gave a detailed description of these (1913) and I therefore refer the reader interested in the structural details to his work and to the adjoining fig. 31—35.

The general development and occurrence of *Pilothrix* in the reefs is quite different to the *Sphaerocodium* in the stratified limestones. In the latter, e. g. in the so-called Sphaerocodium beds, the algae formed round lumps or warty balls with the algal filaments arranged concentrically around the nucleus. In the reefs the corresponding algae, *Pilothrix,* is never seen in this form but as a layer or thin coating on previously formed calcareous bodies. The different development may be explained in the following manner.

[1] From πιλος felt and τριχος hair, cf. *Diehothrix*, *Schizothrix*, etc.

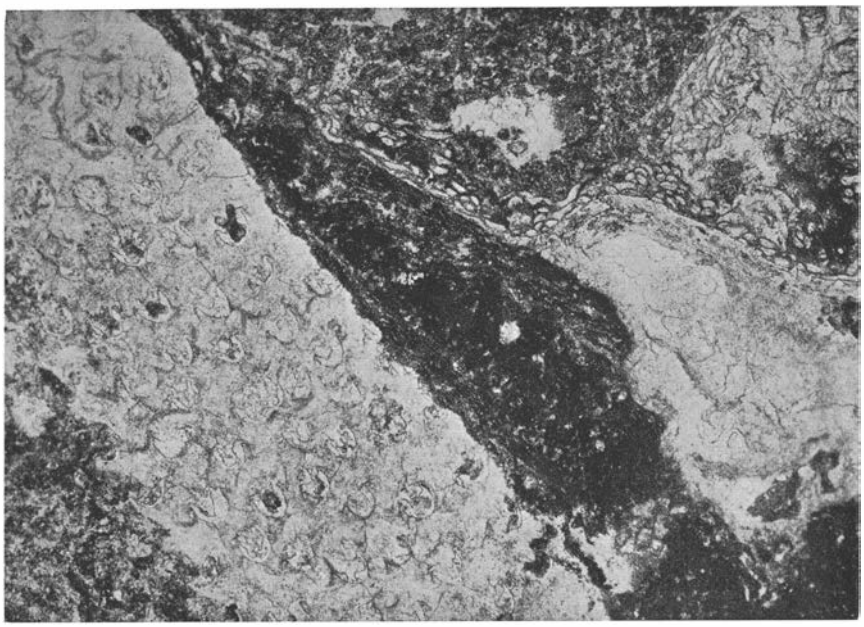


Fig. 32. Matrix of reef limestone with bryozoan fragments and calcareous algae. Ire. (Pr. 5353, pl. 1047). — 17 ×.

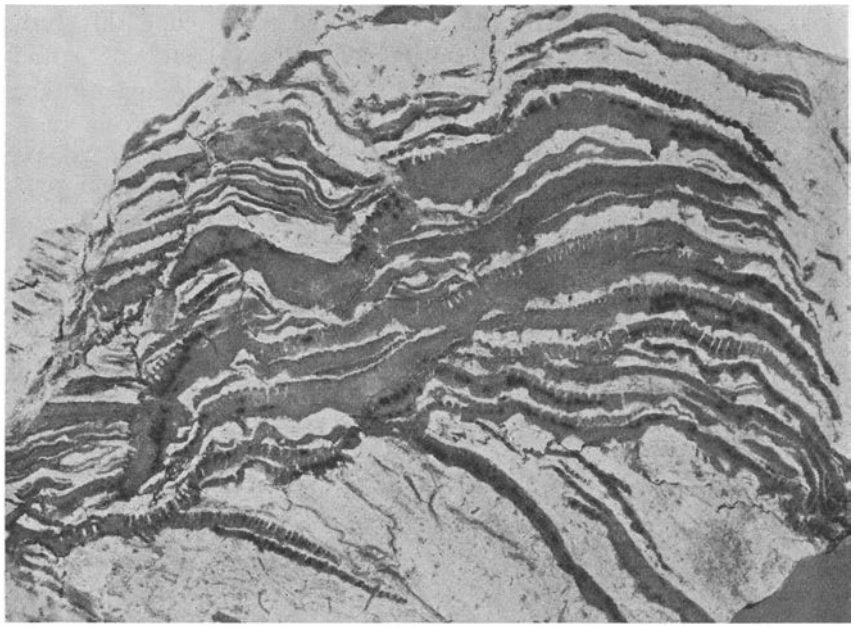


Fig. 33. Reef limestone with *Thecia* (dark) and calcareous algae (light). (Cf. p. 40). Visby. (Pl. 1041). — 1/1.

The concentric structure of the balls derives from their continual change of position; they rested sometimes on the one, sometimes on the other side, and their growth, which always took place in the upper free part, was therefore practically equally rapid on all sides of a ball. If, on the contrary, the algae had been attached to the firm reef, no concentrically growing spherical ball could be formed. The algae could only grow broader and higher and formed a gradually wider and thicker crust on the substratum.

In many cases the algae soon succumbed, either buried under mud or overgrown and suffocated by other lime-forming organisms. Pilothrix limestone consists generally of an insignificant layer, not frequently less than 1 mm thick.

In other cases the algae thrived for a longer period and formed covers several centimetres thick (fig. 33). As a rule, however, the algae played rather the part of covering and cementing than of building material in the reefs, even where these are best developed.

Symbiosis.

The occurrence of algal lime-crusts together with certain corals was pointed out above (p. 33) and should be further emphasized, not least on account of the uncommonly large development of the algae in this society at some places.

In a few small reefs in the Högklint stage south of Visby tabular corals, especially *Thecia*, are found together with an abundance of large stromatoporoids. Their growth lamellae are sometimes separated by a white, macroscopically structureless calcareous mass (fig. 33). Under the microscope this turns out to consist of algal filaments in typical development (fig. 34). A closer study of the limestone shows that the coral colonies and the algae replaced each other with an almost rhythmical regularity and in this manner deposited covers of algal and coral limestones alternately. It may be observed in sections of this limestone and in the microscopical preparates how these organisms began to grow almost spontaneously all over the surface covered by them. The changes in structure and cellular character taking place during growth may be studied in a number of coral as well as algal beds in one and the same sample (fig. 35). The large, vesicular basal cells of corals found in every bed overgrew the algae rapidly, whereupon the bed with the fine vertical tubes was built up. When algae had again covered the corals after a time their rootlets bored down along these tubes and perforated the surface of the corals.

For the estimation of the milieu in which the reefs were formed the calcareous algae are of a certain importance. They are the only reef builders of which we may safely assert that they developed in shallow water, above the lower light and flora limit.

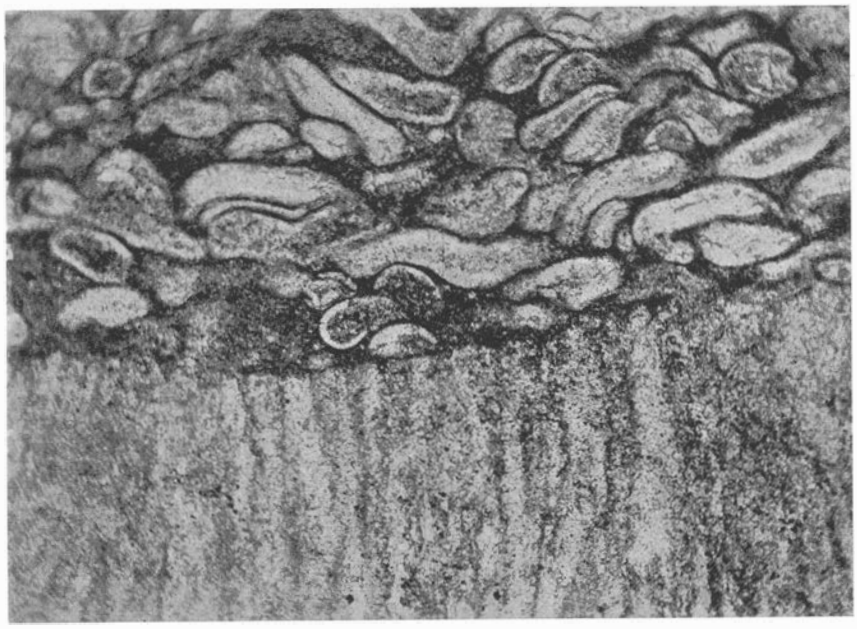


Fig. 34. *Thecia* tabula covered by algal layer with Sphaerocodium structure (*Pilothrix*). Visby. (Pr. 5403, pl. 1038). — 60 ×.

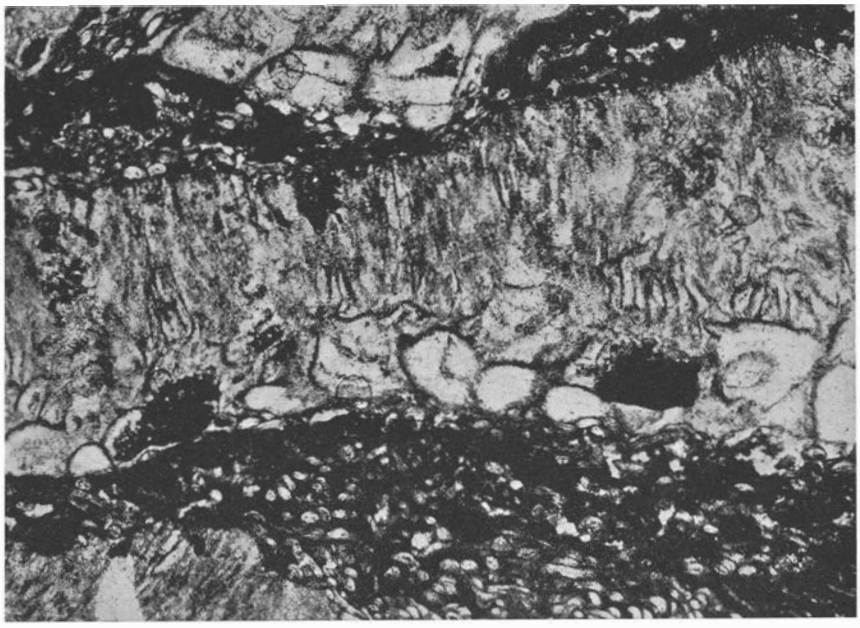


Fig. 35. Alternating layers of algal and coral limestone. Visby. (Pr. 5403, pl. 1060). — 17 ×.

Reef-Building Organisms: Summary.

If, after the above short survey of the different reef builders, we try to sum up the observations on their cooperation and reciprocal occurrence in the reefs, we find the following: —

1) The solid framework of the reefs is never built up of pure stocks. In all the reefs organisms of different kinds and varying in numbers contributed to their construction.

2) In most Silurian reefs of Gotland the stromatoporoids are clearly dominant, and also in cases where their contribution to the reef-building is less obvious a closer investigation will show that it is a peculiar or little noticed development in the stromatoporoids which is the essential cause of the uncertainty.

3) Corals occur in all the reefs of Gotland, often abundantly and sometimes dominantly within locally limited reef portions. The tabular corals are of greater importance as reef builders than the branched ones, although the latter may occur in large stocks.

4) Only under special circumstances (favourable embedding) could the bryozoans form part of the reef-building in their primary position and an undamaged state.

5) Calcareous algae are present in the reefs in varying numbers, partly as irregular lumps, partly and dominantly as covers on and inclusions in the calcareous mass.

6) The stromatoporoids, the tabular corals and the calcareous algae are the organisms that formed the primary solid reef-building.

Other Organisms of the Reefs.

Besides the reef builders proper the fossil reefs contain an abundance of remains of other lime-forming organisms. With regard to their primary occurrence they are of two kinds, viz. partly forms grown on to the reef that cannot be counted among the reef builders, partly forms living free (unattached) on the reef. To the former kind several corals and bryozoans belong (occuring only in insignificant colonies) crinoids, etc., to the latter belong crustaceans, gastropods, lamellibranchs, etc.

Irrespective of certain corals and bryozoans grown on to the substratum, remains of all the above-mentioned organisms lie embedded in the mud deposits and accumulations of fragments amassed in the interior of the reefs and in their immediate vicinity. They are mixed with fragments of the reef builders, with calcareous mud, and with inorganic, mainly argillaceous detritus.

In this connection I cannot forbear to call attention to the fact that the fauna in the hard parts of the reefs is generally less known than that in the looser rocks. The explanation is that the fossils are as a rule better preserved and easier of access in the more or less marly beds than in the mostly hard, splintery limestones containing the sessile reef fauna.

As pointed out above the generally strong recrystallization of reef limestone deleted the finer primary structural features and thus made a study of the fossils more difficult. This is especially true of the stromatoporoids but also of corals, calcareous algae, bryozoans, etc. How abundant in species this fauna and flora are has not been investigated.

In cases where the organisms have an external habit allowing of an identification of species they have also attracted more attention. Thus LINDSTRÖM and HEDE mention a number of different forms of brachiopods, lamellibranchs, and gastropods from the reefs of Gotland. Cephalopods and crustaceans, ostracods as well as trilobites are also to be found, though in less abundance. Amassings of great quantities of a species are only seldom found in the reefs, but together these different calcareous organisms form a rather considerable ingredient part of the reefs.

Certain organisms occur mostly broken into fragments in the reefs. It has already been pointed out that this is the case in the fine-branched bryozoans. In a still higher degree this is true of the crinoids. The latter are not absent in any of the Gotland reefs, and the fragments of their stems and crowns form one of the most common identifiable ingredients in the filling material, the matrix, of the reefs.

Matrix of the Reefs.

The matrix of the reefs is of interest not only on account of its content of fossils but also from a petrographical point of view. It will be the subject of a short discussion in the following.

The fossil reefs were, like the recent ones, somewhat elevated above the surrounding parts of the sea-bottom and on that account specially exposed to the disintegrating action of the waves and currents. Large amounts of fragments were torn loose from the reefs, broken up and partly pulverized, sank to the bottom and were mixed with remains of the benthogenic organisms of the reefs. All the interstices between the reef stocks were filled in this way.

An examination of the matrix shows that it varies greatly. It consists in some places almost exclusively of a fine calcareous mud with scattered small fossils, in other places of coarse fragments from the reef. A fine-grained or dense limestone was formed in the former case, a conglomerate or a coarse fragment limestone in the latter (fig. 36). A matrix rich in clayey mud, a usually greyish green, not very hard marl, may also be found. In most cases, however, the filling consists of a mixture of fossil fragments and mud widely varying in composition (fig. 37—38). Here and there it may grade into fairly pure crinoidal limestone or marl rich in crinoids.

The changes in the character of the matrix are often as noticeable in one and the same reef as in different reefs. Irrespective of differences caused by the changes of the fauna and flora from one stage to another or by the variation of type of the reefs, the matrix is practically alike in all the reefs. As mentioned above it

may in some cases have become the most solid part of the reef which best resists disintegration. Its solidity is due to the fact that the fine calcareous mud recrystallized and formed a firm limestone. This diagenetic process, however, did not result in the formation of coarse calcitic aggregates, as a rule the mass retains its microcrystalline texture.

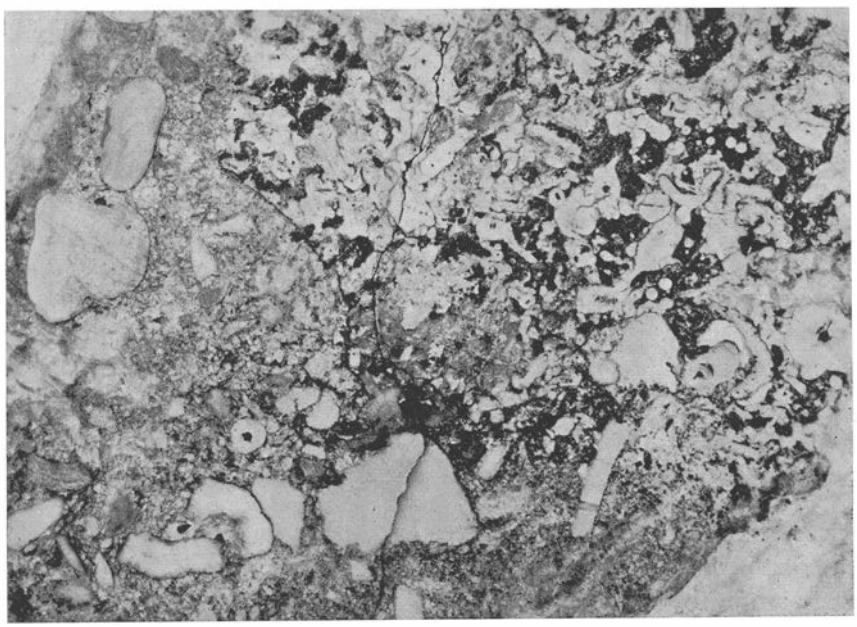


Fig. 36. Coarse-grained matrix of reef limestone. Högklint stage. Ire. (Pl. 1077). — 1/1.

The hardening of the calcarous mud may also have taken place during the deposition, if calcite also crystallized simultaneously from the no doubt saturated solution in which the mud was deposited. It is impossible, however, to draw any conclusions from the nature of the rock as to the importance of the authigenic sedimentary formation of calcite compared with the secondary, diagenetic one. The result of the one should be practically the same as that of the other.

Diagenesis of the Reefs.

Besides the diagenetic process referred to above, by which the matrix of fine calcareous mud occurring in the reefs underwent recrystallization or cementation and hardened, several other phenomena are found in the reefs which must be ascribed to diagenesis. Only one of them is distinctly visible, viz. the usually strong recrystallization of the reef builders and other fossils. It is particularly remarkable that the chemical composition of the reefs is not altered during the

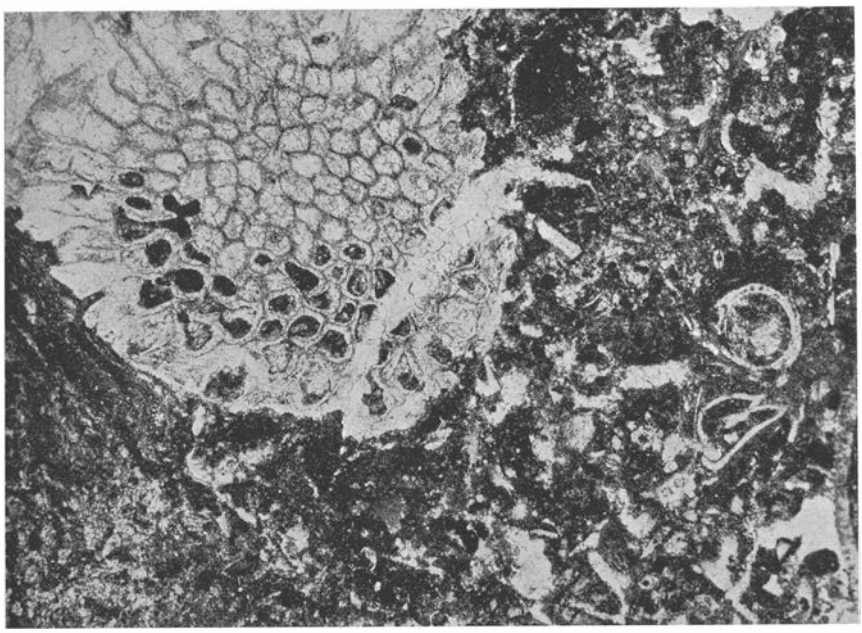


Fig. 37. Fine-grained matrix with bryozoan fragments. Reef limestone of the Högklint stage. Ire. (Pr. 5354, pl. 1046). — 17 ×.

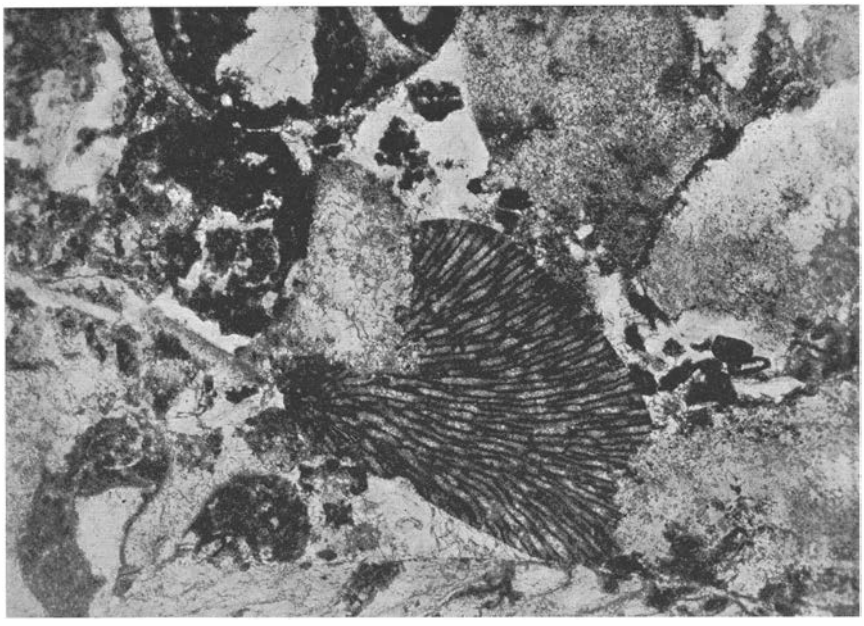


Fig. 38. Matrix of reef limestone. Högklint stage. Visby. (Pr. 652, pl. 1050). — 17 ×.

diagenesis. For I am bold enough to infer that the content of magnesium which is here especially concerned, could not be less in the newly formed Silurian reefs than in the recent ones.

The diagenetic recrystallization of calcium carbonate in the stromatoporoids and in certain corals was often so strong that it extinguished the finer microstructure. Only the granular calcitic matter is seen in thin sections. (In such cases the structure is best visible, if the sections are thick, preferably 0.05—0.1 mm. Their thickness should exceed the diameter of the grains of calcite.) Mistakes are easily made in determination of the fossils. I would specially emphasize that the tabular corals may be mistaken for stromatoporoids or vice versa when their primary microstructure has disappeared. The diagenetic recrystallization makes an extremely detailed and careful examination of the reef material necessary, if one wishes by means of this to form the correctest possible idea of the part played by the different reef builders.

On a comparative study of the corals in the reefs and the same or nearly related species in the marly shales one is struck by the different modes of preservation shown by them. The corals embedded in marl are as a rule far less changed. The even universal pressure in the marls rich in clay and in the first place their slight permeability to water modified the recrystallization process.

The Gotland series of strata was never subjected to a general folding or other powerful disturbances.[1] Consequently the diagenetic processes were not intensified by orogenic forces.

The pressure to which the strata were subjected was greater at an earlier period than now, partly on account of thicker sedimentary covers and partly, during the glacial period, by the inland-ice. No particularly great thickness of the strata removed by erosion which once covered the Silurian of Gotland, is, however, to be taken into account. A diagenesis intensified by a depression of the sediments to a great depth must therefore not be presumed. Nor is there any reason to infer the occurrence of post-Silurian eruptives in the immediate neighbourhood of Gotland. The sediments show no traces of alteration besides the diagenetic changes.

Structure of the Reefs.

Massive structure.

When the reefs are built up of elements with varying or indeterminate orientation they are here called massive. They contrast sharply with the surrounding stratified rocks. In such reefs vertically extended reef builders, for instance branched corals and bryozoans, as well as horizontal ones, for instance tabular stromatoporoids and corals, may appear; but they occur in such an alternation

[1] Around the reefs local movements often occur in the strata: -- foldings, dislocations, brecciation, etc. They are caused by the uneven pressure of the reef on the substratum or the lateral rocks.

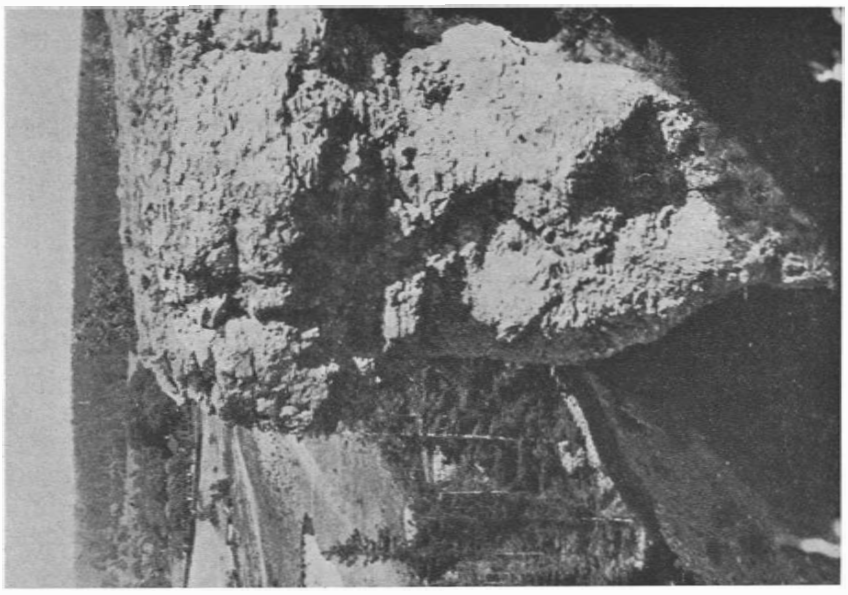


Fig. 40. Massive reef. North side of Högklint by Visby.

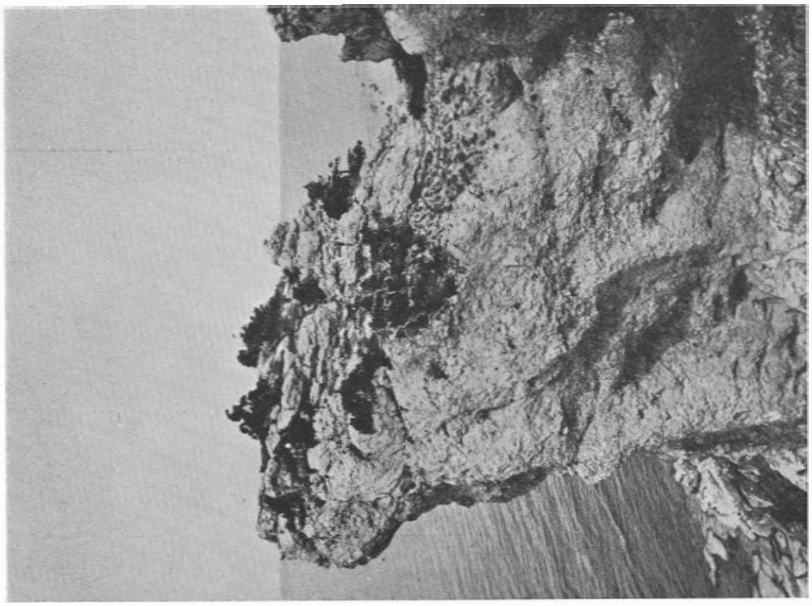


Fig. 39. Massive reef. The large klint E of Ire bay.

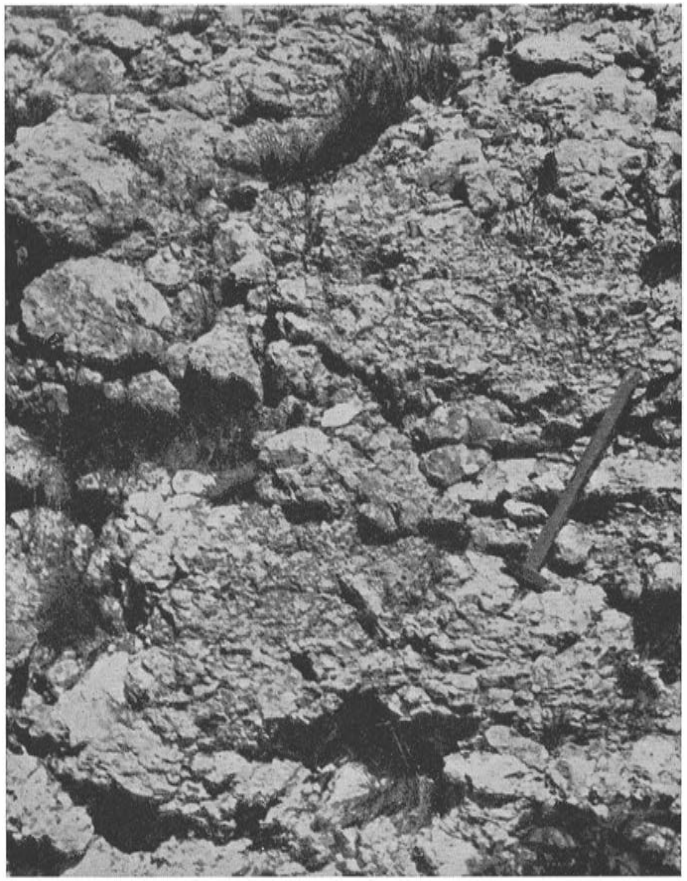


Fig. 41. Reef limestone with conglomeratic structure. Large rounded stromatoporoids and corals. Galgberget. Visby.



Fig. 42. Conglomeratic part of a Gotland reef. Rounded large stromatoporoids in a mass of small stromatoporoids, corals, bryozoan and crinoidal fragments. Large klint E of Ire bay.

with each other and with other material that they do not influence the structural picture.

The matrix is of varying kind and form. It has generally massive, more infrequently stratified structure. If the reefs are well cemented, they form projecting cliffs, »klintar» (fig. 39—40), on the recent as well as the ancient shore-lines. In many places where the abrasion was strong isolated remains of these reefs are left in the form of stonepillars, »raukar» (see p. 78 and fig. 60—62). The massive



Fig. 43. Brecciated stromatoporoid limestone. The reef of Galgberget, Visby. Section 1 m².

structure is especially conspicuous in reefs built up by small stromatoporoids and corals.

Some of the typical reefs show a high content of marl. These forms are abundantly represented, especially among the small reefs that lie enclosed in marly shales (e. g. in the Upper Visby marl). Through the lenticular but as a rule very irregular shape of the embedded marl the massive structure of these reefs sometimes grades into a bed-like one.

Conglomeratic structure.

The structure is conglomeratic in several massive reefs. The rock consists of bun-shaped stromatoporoids and corals together with large amounts of loose material, fragments and fine detritus. Especially on weathering the conglomeratic structure of the rock is strikingly distinct (fig. 41—42 and fig. 13, p. 21).

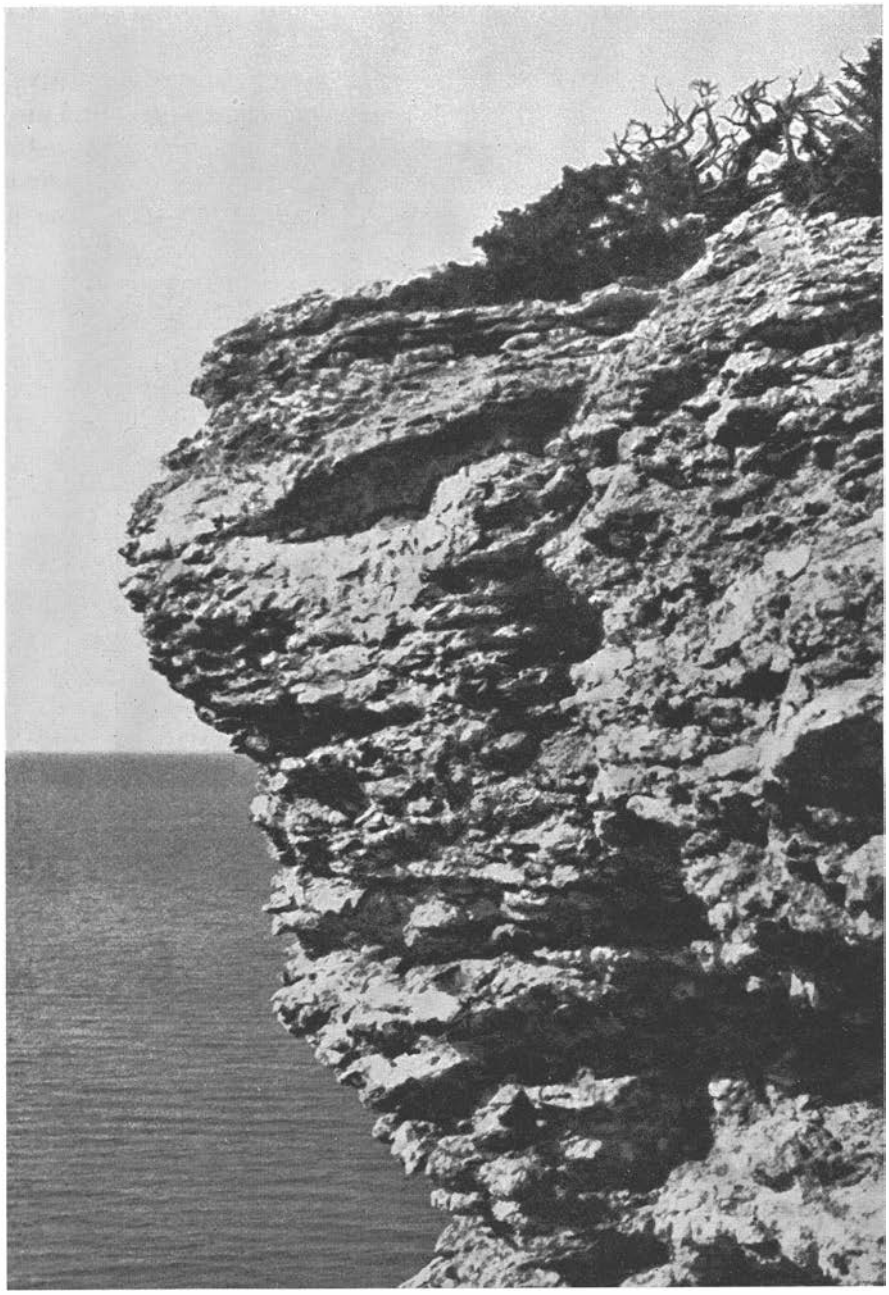


Fig. 44. Slightly stratified marly parts of a stromatoporoid reef covered by fragment limestone. Högklint, Visby.

Brecciated structure.

The brecciated reef structures should also be counted among the massive ones. The limestone in the reefs was probably fairly brittle already in its primary state and has been of slight solidity also after the recrystallization. The rock could not carry its own weight but broke to pieces. The result was that the parts were moved

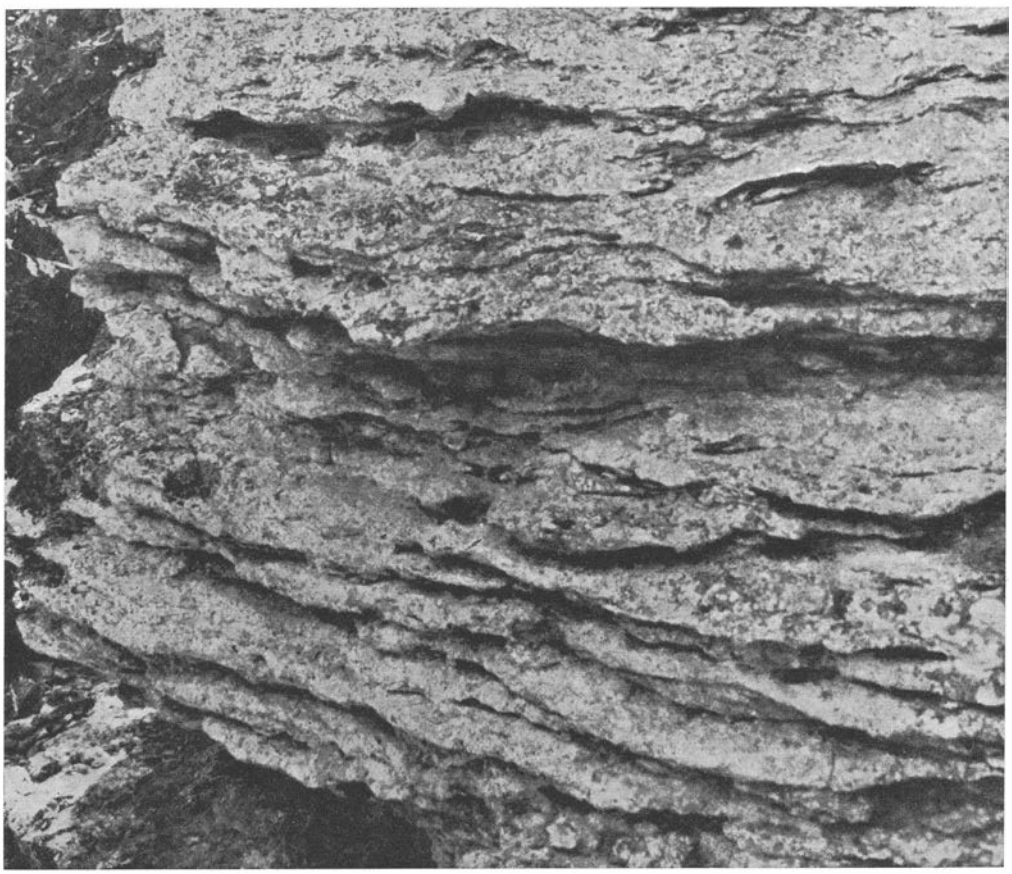


Fig. 45. Reef limestone built up of tabular stromatoporoids and corals. There is no stratification though the matrix as well as the reef builders may give the impression of an irregular bedding. Spangar, St. Karlsö.

a little apart or otherwise dislocated in relation to each other. As a rule the movements were small and the resulting fissures are insignificant, but the rock has nevertheless obtained a characteristic brecciated structure (fig. 43).

Bed-like structure: a) due to embedded loose material.

If a reef obtains a repeated and remaining deposition of loose sedimentary material during its growth, be it of calcareous mud, fossil fragments or inorganic detritus, an alternation between these sediments and the limestone formed by the

reef builders arises. This may be observed in the peripheral parts of most reefs and not infrequently in the interior of them also. The result is a rock in which the stratified structure is more or less visible (fig. 44). This rock should be regarded as belonging to the reef only when it was essentially formed by reef builders and has a distinct organic connection with the normally developed reef mass.



Fig. 46. Reef limestone built up of tabular stromatoporoids and corals. The fig. shows the same reef as fig. 45 but the limestone is more compact. Spangar, St. Karlsö.

Bed-like structure: b) due to tabular reef builders.

The Gotland reefs show one more type with bed-like structure. It is not the ingredient loose masses of sediments in it that have formed the »beds» but the reef builders themselves instead. As they have a flat, lenticular or tabular form the structure of the reef will be characterized by them. This fact was elucidated above in the discussion of both the stromatoporoids (p. 25) and the corals (p. 29) and I shall here only refer to the adjoining figs. 45 and 46, as well as fig. 18 on p. 24.

Relation of the Reefs to the Bordering Stratified Rock.

The boundary between a reef and the surrounding rock may be indistinct. As is evident from the preceding chapter this is the case when the reefs in the periphery are interbedded with strata of the same kind of sedimentary material as that forming the adjacent stratified rock.

On the other hand the reef body is not infrequently found distinctly limited. In such cases it may either lie »exposed» in e. g. marly beds or be enclosed in a special kind of limestone. In the following I shall give a short account partly of the contact conditions at the base and the upper surface of the reefs, partly of their cover of fragment limestone.

The reefs require no hard, mud-free substratum for their development. In many, perhaps in most, cases they have one, consisting of fossil fragments washed free; but reefs resting directly on mud rocks are also found. It was pointed out in the discussion of the reef-building organisms that these may show a peculiar form at the base of the reefs, and that this is not the same if the substratum consists of mud as when it consists of coarse fragments. The downward or lateral bend of the strata underlying the reefs is of course also different according to the tenacity and plasticity of the substratum. The relation between the reef and the substratum was more or less disturbed by the depression. The disturbances are strongest in reefs with a pronounced conical shape; they are hardly noticeable in the lenticular reefs with a wide base.

Not infrequently the oldest part of the reefs has also a substratum of bedded limestone rich in crinoidal fragments. Such limestone is still more frequent under and around the younger parts of the reef. The occurrence of crinoids in mass around the reefs of Gotland is such a common phenomenon that it even tempts us to the conclusion that the reefs are normally surrounded by crinoidal limestone. It would be absurd to attempt a description of the reefs without mentioning the accompanying crinoidal limestone. I shall therefore illustrate its nature and occurrence by two examples.

The best known of all the crinoidal limestones in Gotland is that occurring at Hoburgen and forming the main part of »burgen». This limestone, widely spread as »Hoburgen marble» in the form of polished fancy articles, is a pigmented, reddish brown or mottled, highly crinoidal, relatively dense, and tenacious rock. It surrounds the reef and here and there beds of it dovetail into the reef. The growth of the reef has been uneven, and consequently the contact between the reef and the bedded crinoidal limestone shows an extremely irregular course (Munthe 1910, fig. 20 and Twenhofel 1926, p. 224, fig. 17). In this respect the conditions at Hoburgen may be regarded as typical.

At Korpklint north of Visby the upper part of the cliff consists of reef limestone (fig. 47). The reef has practically the form of a cone (turned upside down) with a very obtuse top angle. The lower part of the section consists of stratified

marlstone. Between the base of the reef and the marl there are beds of fragment limestone of varying thickness (fig. 48). Close to the reef these beds are developed as crinoidal limestone. According as the reef grew in height and breadth it covered

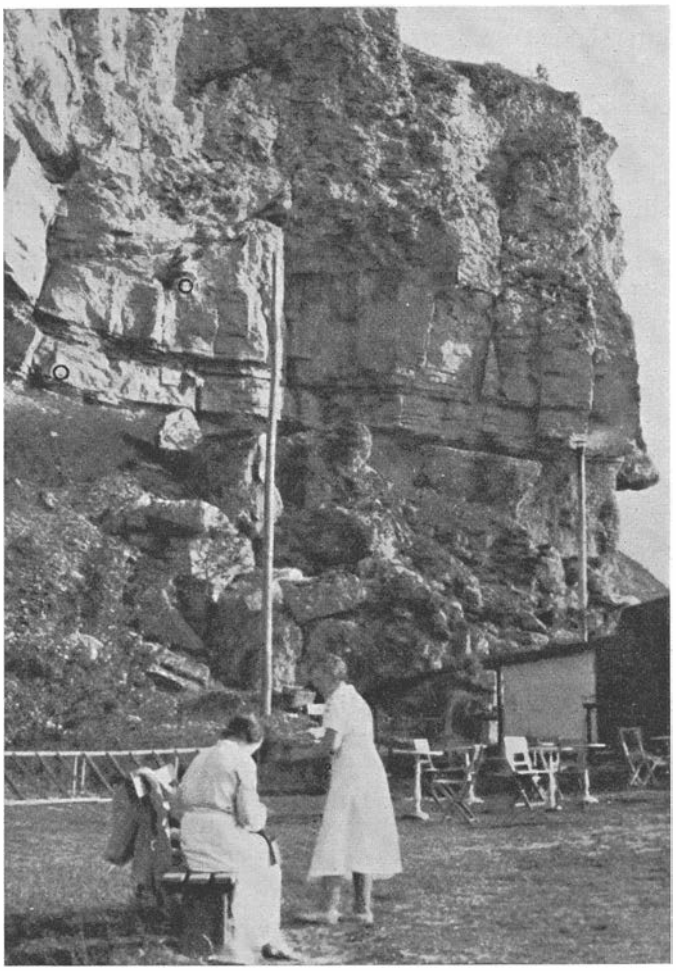


Fig. 47. Typical reef klint of NW Gotland. In the section is seen: Reef limestone (uppermost part of the cliff), crinoidal limestone, fine-grained fragment limestone, marlstone. See also fig. 48. — Korpklint, Visby.

the adjacent parts of the crinoidal limestone and at the same time a new and wider circle of this stratified rock was formed.

Strata of highly argillaceous detritus, which separated the beds in the crinoidal limestone from each other, were deposited time after time. Marl and fragment beds were deposited on parts of the reef surface itself too. It has not been possible to

ascertain whether this deposit suffocated the reef builders or they were killed in another way, for instance by the drying of the reef surface. There is reason to suppose that the growth came to a complete temporary standstill also in other reefs, where fragment beds divide the limestone body into one or several strata. The »planes of stratification» in the St. Karlsö reef were probably formed in this way (fig. 49).

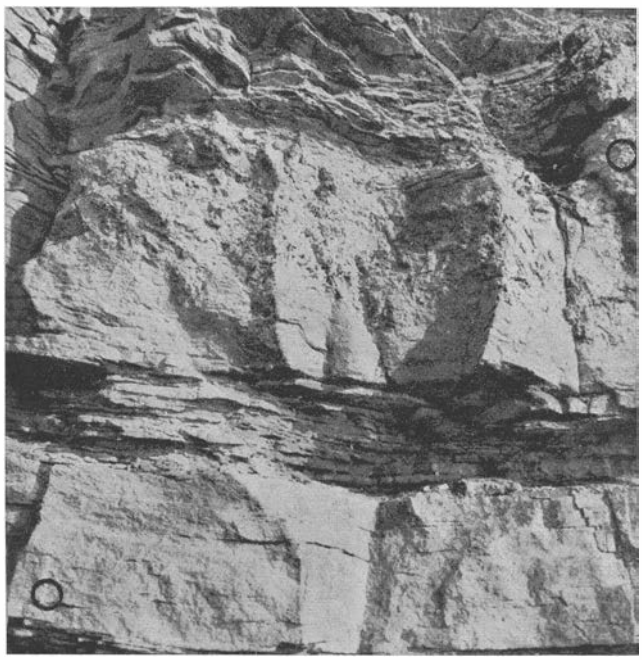


Fig. 48. Stratified limestone below a reef. Detail of fig. 47. In the section is seen: Thin-bedded crinoidal limestone, thick bed of crinoidal limestone with fragments of stromatoporoids and other reef builders, laminated limestone and marl, fragment limestone. Korpklint, Visby.

How much did a reef rise above the loose sediments deposited around it? It is possible to conclude from different facts that the surface of the reef cannot have lain more than at most a few metres above the fragment gravel. The thickest reefs, which have the shape of a reverse cone, would not be able to remain in this position, if they had not been almost completely embedded in sediments formed at the same time as the reef. The often very extended upper part of the reefs did not project freely into the water. I have ascertained in several places that the stromatoporoids and corals in the projecting parts of the reef grew on the underlying sediments. The beds of the bordering rock, the crinoidal limestone, which dovetail into the reef, must be younger than the parts of the reef on which they rest, but judging from my observations they are distinctly older than the overlapping parts of the reef.

When a new reef begins to grow up beside an older one the substratum of the new reef must of course already be completed. Supposing that the surface of the new reef lies on a level with the surface of the older one, the stratified beds must have grown at the same rate as the reefs. If the younger reef has gradually grown together with the older, as is often the case (fig. 50), the relation between the reefs and the surrounding beds is still more obvious.

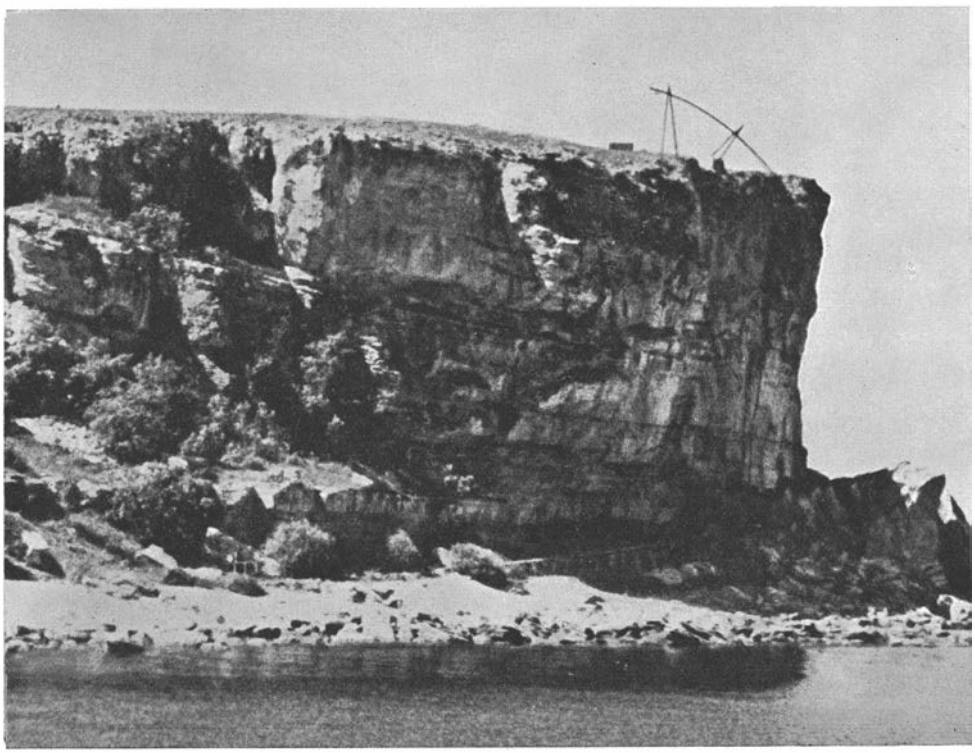


Fig. 49. Big reef with »planes of stratification». Details of this reef are shown in fig. 45 and 46. — Spangar, St. Karlsö.

We may find one more proof of the last-mentioned fact. It is very common that corals or stromatoporoids forming the exterior lateral part of a reef occur in such a manner that they may safely be alleged not to have grown on the older parts of the reef but on the fragments around it (fig. 51).

The crinoidal limestones surrounding the reef are as a rule stratified. When marl is more abundant in them their strata are thinner and very distinct. Strata of crinoidal marl may sometimes occur, also in or in immediate connection with the reefs (fig. 52—53); as a rule they also contain stromatoporoids, corals, bryozoans, and other fragments washed out from the reefs.

Crinoidal fragments accumulated in cavities in the reefs or at another protected place are often devoid of stratified structure. Like the crinoidal sediments surrounding the reefs they may be rich in marl and various fragments. If they were strongly cemented they now may occur as ruins of reefs the rest of which was broken down (MUNTHE 1921, p. 138, fig. 73).

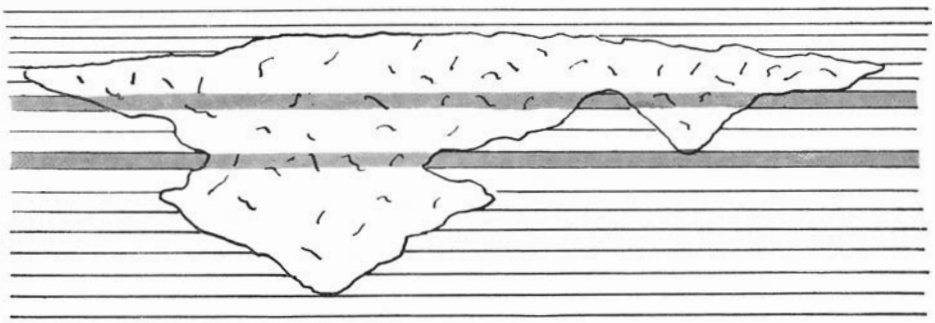


Fig. 50. Diagram showing the contemporaneous formation of two reefs, grown together, and their bordering stratified limestones. The upper parts of the reefs are of the same age, and so are other portions of the different horizons. Before the growing out of the younger reef its substratum has been deposited. This bed must then have had its surface at about the same level as the larger reef.



Fig. 51. Diagram of the boundary between reef and stratified crinoidal limestone. Stromatoporoids, corals and bryozoans of the reef may be seen fixed on the fragments surrounding the reef.

Sometimes the crinoidal fragments near the reefs are preserved in the form of uncemented loose gravel. This is the case in for instance certain parts of the large klint on the eastern side of the Ire bay. In the same klint normally developed crinoidal limestone is also found i. a. as a substratum of the reef. Marly structureless crinoidal limestone is found as inclusion in the body of this reef as well as in others in the same region (fig. 54). The marly inclusions may, however, sometimes show a distinct stratified structure, even if they have only a very limited extent.

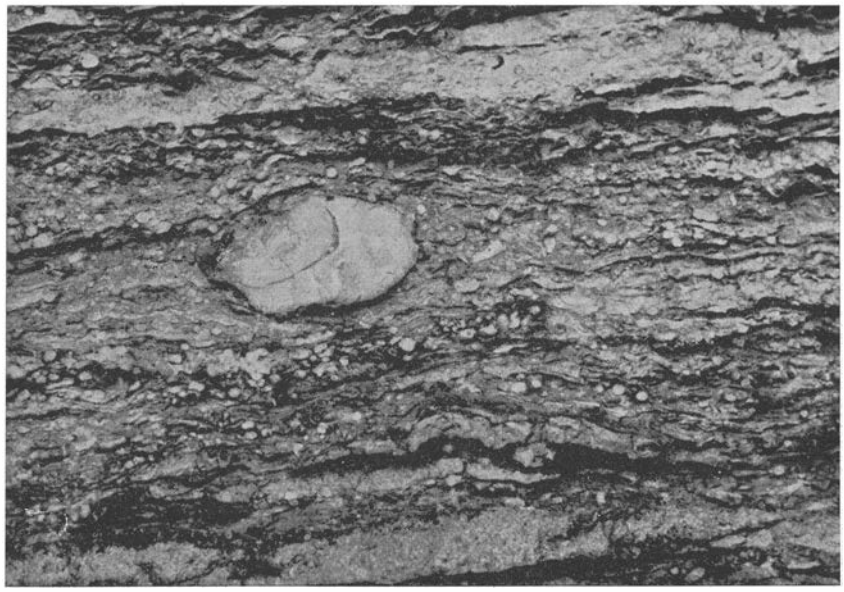


Fig. 52. Crinoidal marl below the Spangar reef, St. Karlsö. Cf. fig. 49. Vertical section.



Fig. 53. Crinoidal marl below the Spangar reef, St. Karlsö. Cf. fig. 49 and 52. Stratification plane.

Sediments directly overlying a reef are generally rich in fragments. As a rule, however, they are not very typical crinoidal rocks, although we know of many examples of such also, i. a. the above-mentioned crinoidal limestone forming the cap of Hoburgen.

In the said, big klint on the east side of the Ire bay the uppermost parts of the reef lie exposed, but its lower lateral parts are covered by a crinoidal fragment

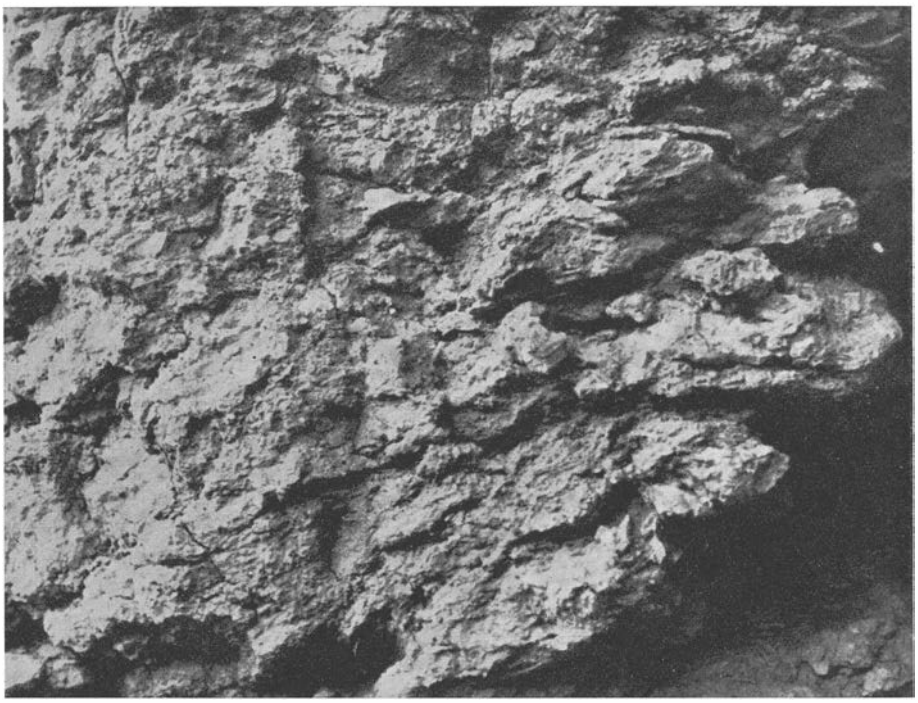


Fig. 54. Marly, crinoidal reef limestone. First klint V of Ire fishing-village.

limestone and this in its turn by a thin-bedded dense limestone. As a rule reefs are covered by the same stratified rocks as occur in the vicinity of the reef and overlie the fragment limestones surrounding the reef. Thus no locally developed sediments associated with the reefs are present in the hanging wall.

Stratified Rocks Equivalent to the Reefs.

The Silurian series of strata in Gotland contains a very large number of reefs which nevertheless occupy only a small percentage of the total rock body. The stratified sediments are dominant in all stages, even where reefs are most abundant. The reefs are locally developed unstratified limestones occurring in certain horizons

of the series of strata. For the investigation of the environment in which the reefs were formed it is important to know also the sediments formed simultaneously with and between the reefs. I shall return to them in a later work on stratified limestones, and I shall here only give a short survey of their general nature.

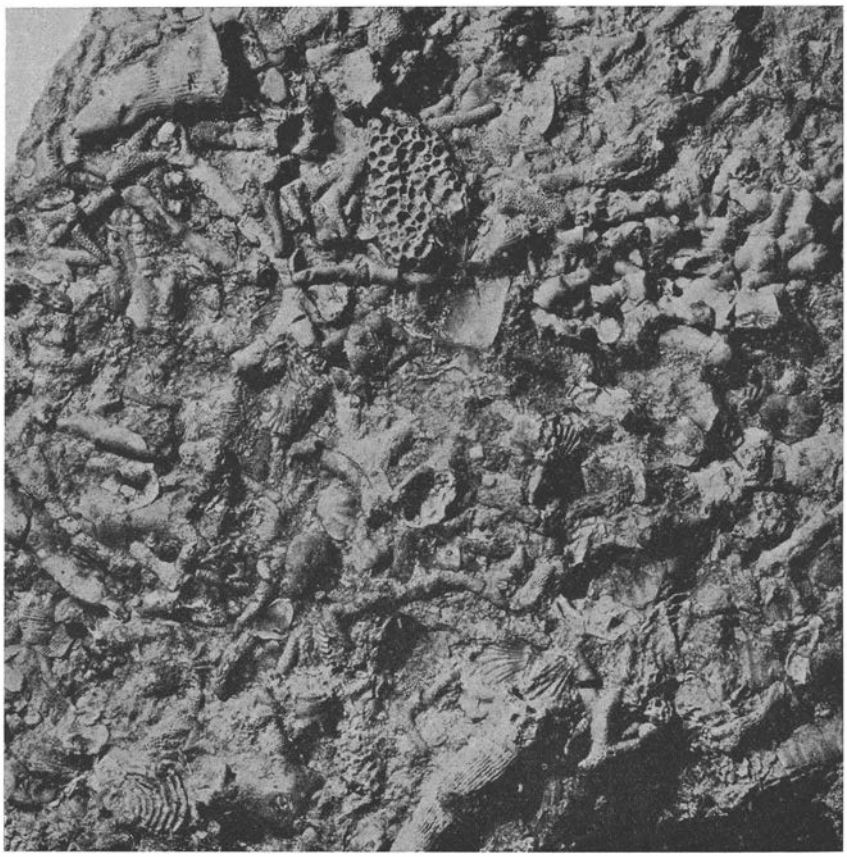


Fig. 55. Stratified fragment limestone. Högklint stage. Halls huk. — 1/1.

No reefs are known from the oldest stage of the series of strata in Gotland, the Lower Visby marl. In the next stage we find about the same petrographical development as in the lower: marl with uneven thin beds or bands of nodular limestone. As a rule this stage is also devoid of reefs. Small reef lumps are found in the marl only in scattered places, i. a. in the waterfall profile south of the encircling wall of Visby and on the east side of the Ire bay. These two stages rich in marl, i. e. rich in inorganic detritus, are thus never rich in and often practically devoid of reefs. This also holds true of other parts of the series rich in detritus, for instance the Mulde marl and the Burgsvik sandstone.

The reefs are very numerous and magnificently developed in the Högklint stage, which contains more limestone and less marl in its accessible parts than the above-mentioned stages. In this stage the stratified rocks vary widely. Marly beds of the same petrographical type as in the Upper Visby stage but also limestones with or without interbedded marl are to be found. These limestones are exceedingly rich in fossils: brachiopods, gastropods, trilobites, corals, crinoids, bryozoans, stromato-

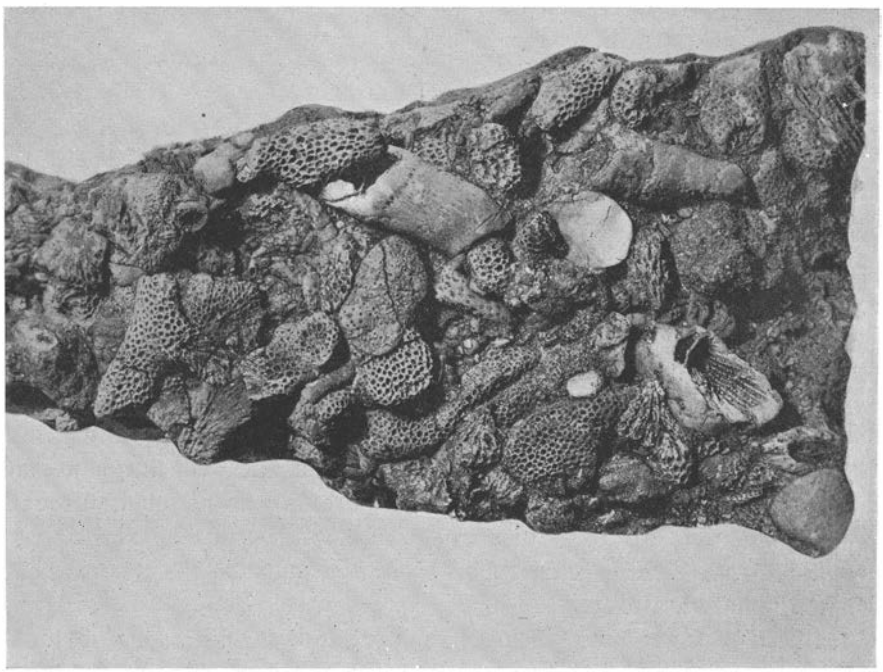


Fig. 56. Stratified fragment limestone. Slite stage. Valleviken. — 1/1.

poroids, and calcareous algae. The fossils occur jumbled together in a manner showing that they are secondarily enriched. A great deal of the calcareous organisms developed on and were embedded in loose mud and were enriched later on by the removal of the mud by waves and currents. In the loose marly beds, separating the beds rich in fragments, the same fossils are found as in the latter, though more widely scattered. In these marly beds the best preserved fossils are to be found, often quite isolated in the loose marl.

Thin-bedded limestones, grey or brown in colour, finely crystalline or granular, sometimes bituminous, often fill up the areas between the reefs. Trilobites, ostracods, cephalopods, and brachiopods are abundant in these rocks and so are bryozoans, crinoids, stromatoporoids, and corals. The material is secondarily redeposited to a large extent.

Further away from the reefs the series of strata usually contains marly sediments with calcareous beds in which practically the same fossils are to be found, although less stromatoporoids, corals, and crinoids but more trilobites and ostracods.

Immediately above the reef-rich Högklint stage the Tofta limestone follows. Its development varies a little but it is characterized by small and middle-sized calcareous algae, specially *Spongiostroma holmi*. Above the large reefs in the Visby region a distinct disconformity is seen and the limestone is partly conglomerate-like with strongly worn fragments of i. a. calcareous algae, bryozoans, corals, crinoids, and stromatoporoids.

Beds of stromatoporoid limestone lie enclosed in the normal sediments of the Tofta stage. These beds have quite a reef-like structure (fig. 9, p. 17) but they are not very thick. As they form a no doubt peculiarly developed but otherwise perfectly normal link in the stratified series they should be classed with this, not among the reef limestones. They tally with the type of limestones, which CUMMINGS (1932, p. 345), termed *biostrom* in contradistinction to the other type *bioherm*, which coincides with the formations I have discussed here under the terms reef and reef limestone.

As is evident from fig. 10, p. 17, the above-mentioned bedded stromatoporoid limestone has no distinctly tabular stromatoporoids and on that account the rock has not the bed-like structure occurring in several reefs (cf. fig. 45 and 46 on p. 51—52). The beds were formed on a spontaneous and vigorous flourishing of the stromatoporoids and by their simultaneous development over large areas of the sea-bottom. Then the whole stock of stromatoporoids was at once suffocated and covered by loose sediments. The occurrence of stromatoporoid beds together with conglomeratic strata rich in calcareous algae shows that they must have been formed in very shallow water.

The stratified rocks in the middle and upper reef-bearing stages of the Gotland series of strata are of practically the same character as those mentioned above. Marly beds and pure limestones, conglomeratic and dense limestones, fragment limestones with a mixed and varying fossil content occur in rich variation. Crinoidal limestone is nearly always found close to the reefs. The marly parts of a stage are most remote from the reefs, as a rule on the south-eastern side of the reef belts. Thin-bedded limestones dominate on the north-western side of the reefs. This distribution of the stratified sediments around the reefs is specially prominent in the two stages, the Slite group and the Hemse group, the reefs of which are marked off on the map fig. 6.

Just as the reefs are somewhat differently developed in different stages and in different places in one and the same stage, the stratified rocks corresponding to the reefs also show great changes. The transitions between the reefs and the stratified sediments show varying forms too. In the Klinteberg stage it may often be difficult to find a boundary between reef and bedded limestone. The same holds true to a certain extent also in the Hemse stage (fig. 15, p. 22), in which, however, the marly ingredient is considerably more abundant. The stratified limestones in

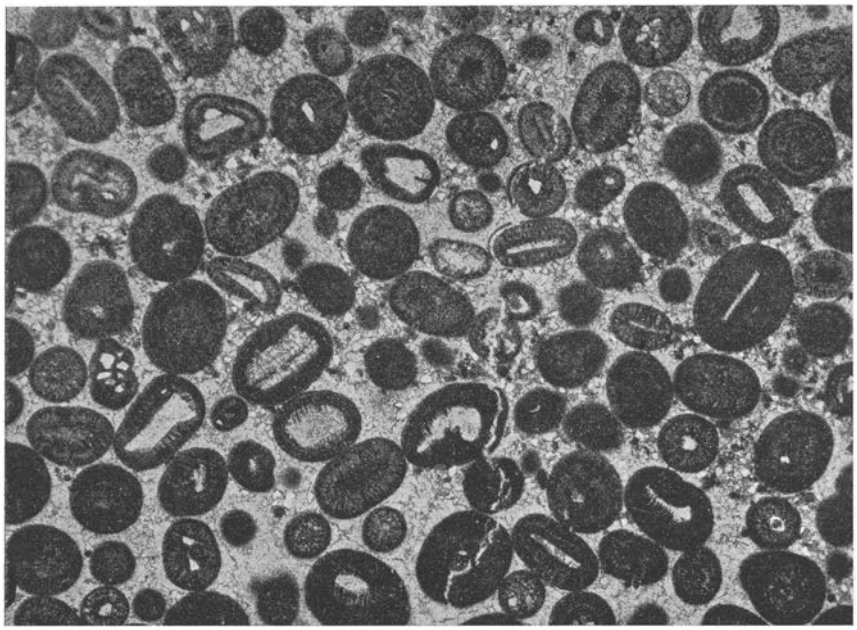


Fig. 57. Fine-grained oolitic limestone. Burgsvik. (Pr. 3337 a, pl. 1078). — 17 ×.

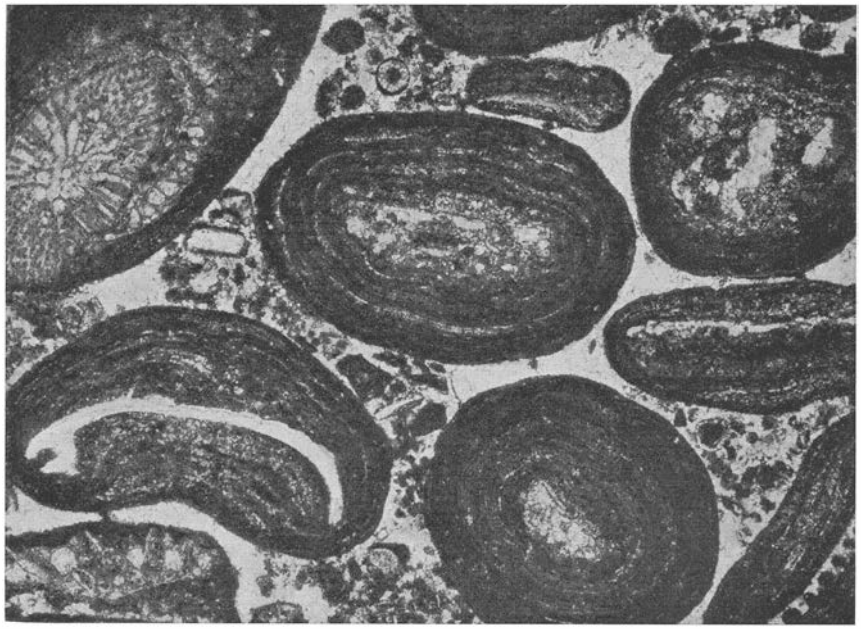


Fig. 58. Coarse-grained oolitic limestone. Burgsvik. (Pr. 3339, pl. 1080). — 17 ×.

these stages are often rich in stromatoporoids and corals, and the limestone in the beds may be nodular and uneven as in the reefs.

Stratigraphical index layers with only slight thickness but with a fairly wide extent occur in different horizons in Gotland. As an example of such layers we may mention the Dayia limestone in the top part of the Hemse stage as well as the Sphaerocodium limestone at the bottom of the Hamra stage.

It should be observed that arenaceous sediments are wholly absent in the bulk of the series of strata in Gotland, and that the present ones nowhere are known as certainly equivalent to the reef limestone. The upper part of the Slite stage contains locally (on the west coast of the island) beds of a calcareous sandstone up to 3 m thick, which rest on a marly shale belonging to the same stage. The sandstone in the Burgsvik stage is considerably thicker (about 40 m). In both stages the rock is exceedingly even-grained and fine-grained and, in some parts, highly argillaceous.

Together with the sandstone we find oolitic limestones, finer as well as coarser, partly conglomeratic (cf. MUNTHE 1910, p. 16 and 1921, p. 38) or with distinct, large ripple marks (MUNTHE 1915). Oolitic limestone has been observed also in other places, though less well developed. Although I shall devote a special study to these rocks in another work I cannot forbear to mention a few words here on their character.

The oolites proper, i. e. limestones essentially consisting of ooids, should not be mistaken for the so-called fine-oolitic or oolite-like limestones often mentioned from Gotland in the geological literature. The grains of the latter consist of rounded fossil fragments or a fine-grained calcitic mass, which may have been formed in different ways though never by a successive growth of or around a nucleus. The ooids, on the contrary, always show such a growth, even if they otherwise vary in size and shape.

The ideal type of ooids, that with a distinct, radially fibrous structure and concentric layers of growth, is not the most common but is met with in different beds in the Burgsvik stage. These ooids are small, rarely more than 0.5 mm in diameter, practically equal in size within a bed. Judging from the structure, their formation may be quite inorganic. They often contain a nucleus of some foreign matter: a grain of sand, a shell fragment or the like (fig. 57).

The most common type of ooids has a relatively large nucleus generally consisting of a fossil fragment and around this a crust of varying thickness. The latter shows no pronounced radial structure but concentric laminae of growth, which follow the outline of the nucleus but tend to give the growing calcareous body a more and more rounded form (fig. 58). In their entire structure these ooids show a striking resemblance to the fossil and recent layers of algal limestone known to us from different quarters and formed as a crust around grains of sand or fragments of different kinds. They appear as miniature models of *Spongiostroma*. The crust

shows no distinct organic structure nor any traces of algal filaments or cellular formations. The ooids resemble *Spongiostroma* in this respect too.

The size of the last-mentioned ooids varies widely; they are generally 0.5—2 mm in diameter. Even if some beds are coarse-grained and others fine-grained, ooids of very different size may nevertheless be found mixed together.

The Gotland oolites are often rich in fossils. Lamellibranchs are strikingly abundant, besides brachiopods, ostracods, trilobites a. o.

The matrix between the ooids and the fossils consists of dense or fine-crystalline calcite, sometimes more or less mixed up with small grains of quartz (about 0.05 mm in diameter). Cement is often so abundantly present that it must have been primarily deposited as calcareous mud.

In the conglomerates occurring within the oolite the pebbles consist partly of stromatoporoids and other fossils, partly of an oolitic mass (MUNTHE 1921, p. 38); the pebbles of the conglomerate are often coated by a crust of algal limestone. They show a distinct *Sphaerocodium* structure.

It is of interest for the study of the formational environment of the Gotland reefs that the sandstone- and oolite-bearing parts of the series of strata are practically devoid of reefs. But it should be noticed that the stages contain marly reef limestones in places where the sandstone and the oolites are least developed, i. e. on the east coast of Gotland. The fauna in these reefs and in the surrounding rocks is of the same character as that found in and near other reefs and consequently fairly different from the above-mentioned one distinguished by lamellibranchs, which was found in the typical oolitic formation. Petrographically as well as paleontologically the oolites and sandstones are typical shallow water sediments, which is further corroborated by the conglomerates, ripple marks, tracks and trails observed in these rocks (cf. HEDE 1925, p. 30, Bl. Ronehamn). In the oolite-bearing stages the reefs occur only within those parts of the series that were deposited in the deepest waters. The difference in depth within the different parts of the sedimentation area could, however, not be great.

The largest and most frequent reefs occur in zones and stages with sediments in a relatively pure or marly limestone facies. Least reef-bearing are marly shales, sandstones and oolites. As was mentioned above, the last-mentioned were formed in shallower waters than reefs and other limestones, the marly beds on the contrary in somewhat deeper waters. The latter is evident from the fact that the stratified limestones consist essentially of fossil fragments, more or less exposed to wave-action and often washed completely free from mud. The paleontological character of the sediments also speaks for a division of the deposits of the area along the reef zone with the fragment limestones and the littoral lamellibranch sediments on one side and with sediments deposited in deeper waters on the other (cf. HADDING

1933, 50). The differences in depth were, however, not very great and the local conditions often played a larger part than the general ones, on which account a generalization is exceedingly dubious.

Formation of the Reefs and Surrounding Rocks.

General Development of the Silurian Rocks in Gotland.

In my account of the reef limestones I had reason to make a few comments on their construction, and in my remarks on the stratified sediments I attempted to emphasize qualities of importance for the interpretation of the environmental conditions dominant during the formation of the reef-bearing series of strata. Guided by the observation material at my disposal I shall try below to give a survey of the general development as well as of the special conditions dominant during the formation of the reefs.

The oldest reefs in Gotland occur in the upper part of the Upper Visby stage but the first great formation of reefs took place a little later, during the deposition of the sediments of the Högklint stage. Consequently the oldest strata in Gotland are devoid of reefs. The questions to be discussed in the first place are, Under what conditions were these strata deposited? and, What changes appeared when the reef-building began?

The Lower Visby stage consists essentially of a distinctly stratified loose marl with embedded bands of thin lenses or balls of limestone. The series was deposited in tranquil water and the sedimentation was rhythmic with an alternation of more argillaceous and more calcareous beds of mud. During the diagenesis the bulk of the calcium carbonate in the latter accumulated in layers as irregular nodules, eventually growing together into flat lenses or thin limestone beds. Consequently the diagenetic processes were the same as in other sediments formed by clayey calcareous mud, but the percentage of calcium carbonate was too low in relation to the percentage of clay for the formation of connected beds (as in dense, bedded limestones etc.) and too high to appear only as scattered concretions.

The Lower Visby stage was deposited in deeper water than the following parts of the series. The fauna does not show the elements characteristic of the littoral formations proper or of the shallowest regions close to the shore. Lamellibranchs are not absent, certainly, but they are only sparingly present. This holds true also of ostracods, bryozoans, crinoids, and stromatoporoids. Of course only such forms of corals were found as thrived in mud and muddy water, particularly *Halysites, Heliolites, Cystiphyllum,* and *Palaeocyclus.* Calcareous algae are absent. There is reason to suppose that the water was too deep for their thriving, certainly more than 50 m.

At the transition from the Lower to the Upper Visby stage we do not find any more remarkable change in the general character of the sediments. The same

marly beds with limestone lenses as form the bottom series continue upwards. The fauna is subjected to certain changes but maintains its environmental character. Corals, bryozoans and stromatoporoids become somewhat more common but the calcareous algae are still absent. This stage was also formed in fairly deep water.

In the Upper Visby stage, however, distinct proofs of a gradual elevation of the sea-bottom are found. Fragment limestones become more and more common in the upper part of the stage. They were formed by the removal of deposited marly layers by currents and waves. Their content of coarse fossils was then left behind. These are found in the series as thin limestone beds filled with mostly well preserved, slightly worn calcareous brachiopods, corals, bryozoan branches, crinoidal fragments, and the like. In places where these limestones are abundantly present within the series the sedimentation took place at so slight depths that strong waves or occasional currents could influence the bottom deposits. The depth was, however, still so great that clayey mud was deposited under normal conditions.

In these top parts of the Visby stages the first reefs appear. They attain a small size only, are rich in marl and but little characteristic. They indicate a locally vigorous flourishing of stromatoporoids and large coral stocks, especially *Favosites, Halysites* and *Heliolites.* The fact that the reefs do not attain a larger or more powerful development is no doubt due to the checking influence of the mud on reef builders, particularly on the stromatoporoids. Marly beeds dovetailing into the reef show that the formation of reefs has repeatedly been on the verge of suffocation before its complete extinction. Only exceptionally do we find reefs in the Upper Visby stage continuing upwards into the Högklint stage.

The elevation of land continued and may be traced in the Högklint stage, i. a. in the gradually thicker fragment limestones. Certainly, marly beds are still present but they alternate with pure limestones. The content of clayey detritus decreases more and more in the sedimentation area. The fauna becomes richer and above all stromatoporoids, bryozoans, lamellibranchs, and gastropods are more abundantly present than before.

The changes in the sedimentation are also greater than before. Environmentally conditioned, locally developed rocks are common: a positive proof of a deposition in shallow water.

In the Gotland series calcareous algae, especially *Solenopora* and covers of *Pilothrix,* occur first in the Högklint stage. Their development implies that the depth did not exceed a few tens of metres.

Here and there in the series we find conglomerates with strongly worn balls of calcareous algae, stromatoporoids, corals, etc. which show a formation in shallow water.

In this series, which was probably formed in depths between 5 and 50 m, reefs are very abundant. I have shown above (p. 56) that the upper surface of these reefs cannot have been elevated more than a trifle above the surface of the sur-

rounding stratified sediments, and we may therefore fix the level for the strongest development of the reef-building organisms between 5 and 50 m.

The elevation of land continued during the formation of the reefs and other rocks in the Högklint stage. The marly deposits become gradually rarer, the fragment limestones gradually thicker, the reefs more and more extended.

Then the reef formation ceases at once. Why?

It is an obvious conclusion that the progressive elevation of land resulted in an elevation of the reefs above the surface of the sea and in the death of the reef builders. This is perhaps what happened, but only for a short time. The reefs are covered by marine sediments, as a rule conformably overlying the stratified rocks deposited between the reefs. These sediments tell us something more of what has happened.

The rocks covering the reef zone of the Högklint stage vary greatly. Fragment limestones, also typical conglomerates with pebbles of the reef body, stromatoporoids and corals, are to be found. Thus a disintegration of the earlier formed rocks took place.

In places where the disintegration had been particularly strong or lasting a slight unconformity arose between the Högklint stage and the overlying Tofta stage. It is visible in some of the exposures within the boundary layers, particularly in the quarries N of Visby, and locally an intraformational conglomerate is found there as a termination of the Högklint stage. The sedimentation following on the transition from the elevation to a depression of land does not immediately differ from the previous one. Fragment limestones dominate. But according as a new flora and fauna develop the deposits are characterized by them. The calcareous algae have a flourishing period, and we find them as a thin coating on fossil fragments as well as in greater quantities. It was particularly the walnut-sized or larger algal limestone balls termed *Spongiostroma holmi* Rothpl. that attracted early notice. They may occur in rather thick, hard limestone beds separated by thin layers of clay. As said before, beds of a relatively pure stromatoporoid limestone occur together with these, but the reefs proper are absent. One may ask the reason for this. The conditions of depth and temperature could hardly impede a reef formation, nor could the content of mud in the water. It is more likely that the salinity or some other chemical quality of the water played a part here.[1]

The stromatoporoid beds of the Tofta limestone show a short but vigorous flourishing of these hydrozoans. It seems as if an occasional change (for instance change of current direction) should have caused these organisms all of a sudden to cover the sea-bottom, and as if they should as suddenly have died out after a new change of the conditions.

Other reef builders which require the same conditions as the stromatoporoids

[1] It is not impossible that the Tofta limestone was deposited within the littoral zone or at such a slight depth that reef-building organisms did not thrive. The conglomerates partly formed from calcareous algae of the Tofta stage give support to such an interpretation. There are, however, no certain signs of drainage.

for thriving did not develop as rapidly. It is thus very remarkable that corals are almost absent in the Tofta stage, and that bryozoans are rare; I do not here consider their occurrence in certain fragment limestones with material from older sediments too. It is also of interest for the estimation of the formation of this series of strata that brachiopods, which for the rest form the most abundant ingredient in all the stratified rocks of Gotland, are practically absent in the Tofta limestone.

The reef-less Tofta stage differs from the older and younger reef-bearing series by the presence of large quantities of calcareous algae and the slight occurrence of corals, bryozoans, and brachiopods. During the deposition of the Tofta limestone the depth conditions were, temporarily at least, about the same as during the flourishing period of the reefs and, judging from the rich deposition of limestone, the conditions of temperature were probably also the same. As a plausible explanation of the peculiar development remains, nevertheless, an occasional elevation of land or a certain change in the physical or chemical qualities of the sea-water, for instance in temperature or salinity. The supposition of such a change seems to me also to agree with the rapid variations that must obviously have taken place. I am not able to state any facts which to a certainty show the cause of the formation of the peculiar reef-less series of strata.

In the preceding I have made an attempt to sum up the changes occurring before, during and after the period when the first large reef zone of Gotland was formed. The course of development has practically followed an even curve. No doubt a closer scrutiny of the circumstances will nevertheless show that the elevation of the sea-bottom did not progress uniformly but under oscillations. The local environment also played a great part. Special study should be devoted to these circumstances, particularly to the distribution of reefs and different types of stratified rocks. I regret to say I must here desist from discussing them.

On proceeding to illustrate the formation of younger reefs and reef horizons in Gotland, I may refer to the fact that the conditions dominant at their formation were practically similar to those under which the Högklint stage was formed. The variations in the sedimentation are repeated and new types are also developed. Stratigraphically interested readers are referred for details to J. E. Hede's excellent, exact accounts of the series of strata in his descriptions of the geological maps (see further p. 90). Hede gives in the same places detailed lists of fossils from different localities and from all the stages. He has also marked the different rocks on the maps. But I must leave these valuable works and restrict myself to my own special investigation.

The reefs of the Slite stage lie, in a still higher degree than those of the Högklint stage, in different stratigraphical horizons. As shown by the map on p. 11 they also occur in different belts. The bottom deposits of the stage are of varying kind, though stratified limestones dominate. These are to a large extent developed as bryozoan limestones and crinoid limestones, partly also as oolite. Especially this part of the series of strata was no doubt deposited in very shallow water. In this connection it should be pointed out that farthest NE the rocks of the Slite stage

rest, as shown by Hede (1936, p. 11), directly on the Högklint stage. The Tofta limestone which otherwise interbeds them is absent. Is there a break in the stratification, as supposed by Hede (1933, 34), or did the relatively unchanged environment only impede the development of the peculiar limestones rich in calcareous algae which are known under the above denomination?

Reefs and reef-like limestones occur already in the lower part of the Slite stage, but not until the middle and upper part of the stage do they attain their maximum development. The bulk of the series — the stage is about 100 m thick — is however rich in stromatoporoids and corals. Locally bryozoans and crinoids are often abundantly present. The stage is petrographically built up not only of the said deposits but in an essential degree of thin-bedded fragment limestones and, especially in its upper half, of marls and marly limestones. The latter lie mainly outside and south-east of the reef belts, which does not exclude the possibility that the younger reefs of the stage as well as equivalent stratified limestones are underlain by marly rocks.

Judging from the rocks, the reefs in the Slite stage were formed at somewhat greater depths than the stratified fragment limestones in the lower part of the stage but at less depths than the marls in the middle and upper part of the stage. The reef belts shown by map (p. 11) were probably formed successively parallel to the strike direction of the stratified rocks simultaneously deposited and probably parallel to the nearest shore-line. It would be an interesting task to study the age relations between the different reefs and reef belts. From the oldest part of the stage we know reefs enclosed in bryozoan and crinoidal limestones, in the area S of Visby as well as on Fårön. In the youngest part of the stage too there occur along its eastern boundary reefs which overlie marls deposited at greater depths. These reefs and the accompanying stratified fragment limestones indicate an oscillation in the later part of the Slite stage.

The reefs of the Slite stage are, like those of the Högklint stage, essentially built up of stromatoporoids, corals, and bryozoans. Besides that they contain an abundance of calcareous mud, fragments and here and there also clayey mud. Their structure and fossil content are of the same type as in the Högklint stage. The variations of the reefs in size and shape may be entirely ascribed to varying local conditions.

The consequence of the elevation, which occurred in the deposition of the youngest part of the Slite stage, and which resulted in the formation of the reefs above the Slite marl, was that still more typical shallow-water sediments were deposited. Thus we find them as arenaceous limestone furthest south in the area (at Klinte and Hejde), and in this region as well as in other places the overlying Halla limestone has a still more pronounced shallow-water character. Oolitic limestones (with ripple marks) and fragment limestones, the latter often rich in calcareous algae (*Sphaerocodium* etc.) are common, but crinoidal and bryozoan limestones with enclosed reefs are also to be found.

The Halla limestone is overlain by an out-thinning bed of marl, Mulde marl,

which locally attains a thickness of up to 20 m. Whether this rock, which indicates a sedimentation in tranquil and probably relatively deep water, was partly denuded before the deposition of the Klinteberg limestone is not known. No support of such an opinion (in the form of fossil conglomerates or suchlike) was brought out by the geological mapping. I shall not here discuss the question of the break in the series at places where the marl is absent and the Klinteberg stage rests directly on the Halla stage. It should be observed that the Mulde marl occurs on the west coast of Gotland in an area where the surrounding stages (the Slite and Klinteberg stages) have a pronounced marly development while the Halla limestone on the contrary has a more easterly extension and lies embedded between the same stages, where these are less marly and more developed as fragment limestones.

In several places reef limestones occur in the Klinteberg stage, but this is essentially built up of thin-bedded limestones. All the latter rocks are typical fragment limestones rich in stromatoporoids, crinoids, corals, and bryozoans besides brachiopods and a number of other fossils. Calcareous algae (*Solenopora, Spongiostroma* and *Sphaerocodium*) are also present, locally even in abundance, just as lamellibranchs (*Ilionia* and *Megalomus*) and ostracods are. The series was formed at slight depth; in the author's opinion in shallower water than that in which the reefs were generally formed. It is characteristic of the reefs in the Klinteberg stage that they often contain larger amounts of clayey mud (marl) than the surrounding stratified rocks. They acted as good mud traps. In several cases the character of the reefs becomes less typical on account of admixed loose sedimentary matter. Reefs in typical development, as at Klinteberg, are rare. In the southern part of the area (and the upper part of the stage) we find still more marly beds forming a natural transition to the marly shales that characterize the greater part of the next younger stage, the Hemse stage.

Besides soft marls the Hemse stage consists of dense limestone in thin nodules and to a less extent of bedded fragment limestone and reefs enclosed in this. The reefs have a limited extension. They occur in an E—W belt as shown by the map (p. 11).

The reefs of the Hemse stage are often relatively small. They contain the same types of fossils as the other reefs of Gotland (stromatoporoids, crinoids, bryozoans, corals), but besides that they hold remarkably large numbers of gastropods and cephalopods. Big portions of the reefs are occupied by a hard, dense mass formed of well cemented calcareous mud, clay and fossil fragments. This reef limestone often shows a reddish brown or flamy brown and green colour and is known under the name of Etelhem limestone. Purely grey reef limestones with practically the same fossil content also occur together with this. For the present I am not able to give any satisfactory explanation of the red colour of the Etelhem limestone.[1]

The reefs of the Hemse stage sometimes attain a considerable size. In many

[1] The red colour may be due to a secondary oxidation process but I have not been able to find any direct support of this (in e. g. traces of an uplift).

cases their outlines were blotted out by the abundant occurrence of reef-building organisms, especially stromatoporoids and tabular corals, in the surrounding stratified sediments too.

The Hemse stage is terminated by an elevation during which a fine-crystalline, thin-bedded fragment limestone (the shaly Dayia limestone) is deposited. Above this follows a series of diffusely stratified, often sandy marl, the Eke marl, obviously deposited in a tranquil but shallow basin. This in its turn is overlain by a thick sandstone series, the Burgsvik sandstone, formed in still shallower waters. In none of these series are reef limestones or typical fragment limestones generally present. The Eke marl is characterized by the calcareous alga *Sphaerocodium gotlandicum*, which is locally able to fill up almost whole beds. On the other hand the Burgsvik stage contains, as was shown in detail already before, fairly considerable limestone formations in the shape of oolites more or less rich in fossils.

In southernmost Gotland limestones deposited in somewhat deeper water follow on the said shallow-water formations. The oldest stratum resting directly on the Burgsvik stage consists of an algal limestone exceedingly rich in *Sphaerocodium gotlandicum* (»the Sphaerocodium limestone»). This is locally replaced by fragment limestone, which may also contain marly reefs with stromatoporoids, bryozoans, corals, and crinoids. These deposits as well as those immediately following are attributed to the Hamra stage. The bulk of this stage consists of stratified limestone, sometimes marly, sometimes purer, often somewhat bituminous. The local occurrence of large quantities of *Spongiostroma holmi* is of interest.

In its upper part, at the contact towards the Sundre limestone, the Hamra limestone is partly developed as a typical crinoidal limestone. The same development is found in the greater part of the Sundre stage. Nowhere do we find crinoidal limestones of such a thickness and such a wide distribution as in this stage. Large reefs lie enclosed in these bedded limestones. As usual the reef builders are also here stromatoporoids, corals and bryozoans, with an abundance of fragments and calcareous mud. The deep reddish brown colour characteristic of this, the youngest, part of the Silurian series of Gotland may no doubt be explained as a result of the rather early uplift of the series of strata. In my opinion the colour should be ascribed to a secondary oxidation process.

The above survey of the occurrence of the reefs and the reef zones in relation to other rocks in the Gotland series was intended to illustrate the general conditions of formation. It seems to me to be evident from the observations that all the reefs were formed at slight depths, below the level for the formation of pure littoral sediments, such as conglomerates, sandstones, oolites, and coarse fragment limestones, but above the level for the deposition of thin-bedded mudstones formed in open water. The upper boundary face of the reefs lies in several cases observed below the level for the strongest development of certain calcareous algae (especially *Spongiostroma*), but it practically coincides with the forming zone of other calcareous algae.

Development of the Reefs.

In the preceding an account was given of the share of the different organisms in the building of the reefs as well as of their development and occurrence. The importance of loose material ingredient in the reefs, i. e. fragments, calcareous mud and inorganic detritus, was also illustrated, as well as the relation of the reefs to the surrounding stratified sediments. In the following I shall attempt to give quite a short description of the cooperation of all the different factors in the construction of the reef.

After the creation of an environment favourable for the formation of reefs, i. e. when depth conditions, temperature, salinity, content of detritus, currents, etc. in a certain portion of the sea had become just such as required by the reef-building organisms, these could develop in large quantities. The environmental changes that made the flourishing of the reef-building organisms possible were sometimes fairly imperceptible, in other cases more manifest, not infrequently considerable. I have shown in the preceding chapter how the stratified sediments reveal to us the nature of these changes.

After the creation of the proper environment the reef builders begin the construction of a reef lump. The development may be such that the reef builders first become more and more common in the stratified rocks, then they build up reefs with only a rude stratification, and finally form by and by a structureless reef. If the development proceeds in this manner, it is impossible to point out a certain point or area as the base of the reef. The reef grew successively up from its stratified substratum. Upwards and laterally it may grade as imperceptibly into bedded limestones. For the study of the reefs this type is of interest as well as others, but it may be regarded as a less characteristic type of reef which was built up under special conditions, and the formation of which requires no special explanation. Therefore I pass on to the first-mentioned type, the »pure» reefs.

Where the base of a reef is visible one generally finds an accumulation of stromatoporoids or tabulate corals which have created a solid ground for continued growth. New colonies attached themselves to older ones and contributed to the growth of the calcareous skeleton. At the same time all the loose material washed away from the reef together with fragments of the lime-forming organisms developing around the reef was deposited around the growing reef lump. These loose deposits which we now find as stratified limestones must have grown at about the same rate as the reefs. As I have already shown (p. 56), the upper surface of the reefs may have been elevated a few metres above the environment. If the reef builders die out the reef may soon be buried in calcareous fragments. The loose material directly enclosing the reef consists essentially of coarse fragments, among which parts of crinoids are as a rule dominant (p. 53).

Within one and the same reef widely different types of reef builders occur. Relatively pure stocks and mass-occurrence of some species or other may be found

locally. As to the fossil content in general we are however seldom able to show any definite change in the organic ingredient during the growth of a reef. For details on the appearance of different reef builders and the part played by them I refer to the above account.

In the preceding attention was called to the large amounts of mud and fragments forming part of the reefs. They give support and stability to the branches of the reefs, and not infrequently they form the most solid portions of the reef after their cementation.

Epeirogenic and Paleogeographic Conclusions.

The changes in level or to put it more exactly the changes in depth conditions evident from the general changes of the rocks were discussed in the account of the Silurian series of Gotland given in the preceding chapter.

The sea-bottom is elevated from a relative depth during the deposition of the Upper Visby marl and the Högklint limestone. The strongest shallowing is traced in the locally developed conglomerate and the slight disconformity between the Högklint and the Tofta stages. Thereupon oscillations follow. The sedimentary changes occasioned by them are often not greater than those caused by variations in the local conditions. I refer to the preceding chapter.

All the rocks of the Gotland series are formed in shallow water, and the epeirogenic movements reflected by them were not great, probably not exceeding some hundreds of metres. As to some of the sediments, I do not venture upon any definite conclusions regarding their formation during an elevation or a depression. This applies specially to the Mulde marl, which may, on account of its petrographical character, be interpreted as a sediment deposited at a relatively great depth while its very limited extension as well as its fossil content, particularly its not slight content of lamellibranchs is more indicative of a formation in shallower water.

The reefs do not indicate periods of depression, as is the opinion of Wedekind and Tripp (1930). But they mark, as was shown above, a certain depth zone within the area of formation. If the sea-bottom was more deeply situated before the formation of the reef, this occurred during an elevation period. The thick reefs within the Högklint stage were obviously formed in this way. If the sea-bottom, on the contrary, was situated at too slight a depth for the flourishing of the reef builders, these developed first in connection with a depression. We find examples of this i. a. in the Hamra and Sundre stages overlying the oolites and sandstones of the Burgsvik stage which were formed in very shallow water.

Reefs were not always formed when the sea-bottom was situated within the depth limits of the thriving of the reef builders during a depression or an elevation. Other conditions, appropriate temperature, salinity, currents, etc. may have been absent. The depression which succeeded the deposition of the shallow-water lime-

stones of the Tofta stage, rich in algae, is not especially characterized by reef formations. After the depression resulting in the formation of the Slite marl, deposited in deeper water, a new elevation begins with a vigorous flourishing of the activity of the reef builders.

It may seem unnatural to attribute the reef-building to a period of elevation, a regression. Under such conditions a growth in thickness would be excluded in modern reefs with their surface on the ebb level. The reefs of Gotland were however not formed immediately below the ebb level but at a somewhat greater depth, estimated at 5—50 m. At an elevation of land the reef itself could grow 20 m high under certain circumstances at the same time as the bottom was equally raised. The shape of the reefs may be connected with the changes in depth conditions which occurred during their growth. When the reef builders had reached a level particularly favourable for their development they did not strive to get above this but spread laterally instead. Consequently the wide extension of the upper part of the reefs does not imply that they reached the limit of their upward growth. But the proceeding elevation of land has of course gradually killed the separate reefs. They were buried below beds of coarser and finer calcareous fragments.

When the reefs were formed on a sinking sea-bottom they mainly strove, their upper surface having passed the level for their most favourable development, to compensate the lowering by upward growth. It would nevertheless no doubt be incorrect to draw any conclusions as to the changes in level only from the extensions or partitions visible in a number of reefs. Every other change in the environmental conditions may have influenced the reef builders and the development of the reef. But the study of the general development of the reefs is nevertheless of importance for the explanation of the epeirogenic movements, and when it is inserted in the general investigation of the other sediments as well as of the nature of the fossil fauna and flora relative to each other, certain conclusions may be drawn.

It would be of great geological interest to know the grouping of the Gotland reefs in relation to a contemporaneous shore. For the present, however, we are not able to reconstruct the course of the shore-line in South Sweden during the latter part of the Silurian period. We know that parts of Scania and central Dalecarlia have the whole time lain below the surface of the sea, and we have reason to suppose that there was an extent of land between these two basins. Probably the coast-line west and north-west of Gotland had a more or less similar course to the present, and it would be quite natural if the sea-bottom inclined slightly towards the east and south-east from this coast-line. If this was the case, the different stages ought to show coarser sediment to the NW and W and finer to the SE and E. Unfortunately the stages in the direction NW—SE are exposed only in relatively narrow zones. On that account no obvious changes in the character

of the sediments in a certain belt owing to the nearer or remoter position of the different parts of the area of deposition from the shore are to be expected. Certainly, the fact pointed out before that some of the stages, especially the Slite and Hemse stage, in the north-western part of the zone of distribution show in the first place fragment limestones and highly argillaceous mud rocks along the south-eastern edge, is indicative of a greater depth of water to the south-east than to the north-west. As long as we have only a few proofs of a contemporaneous formation of the rock deposited in shallow water and of that deposited in somewhat deeper

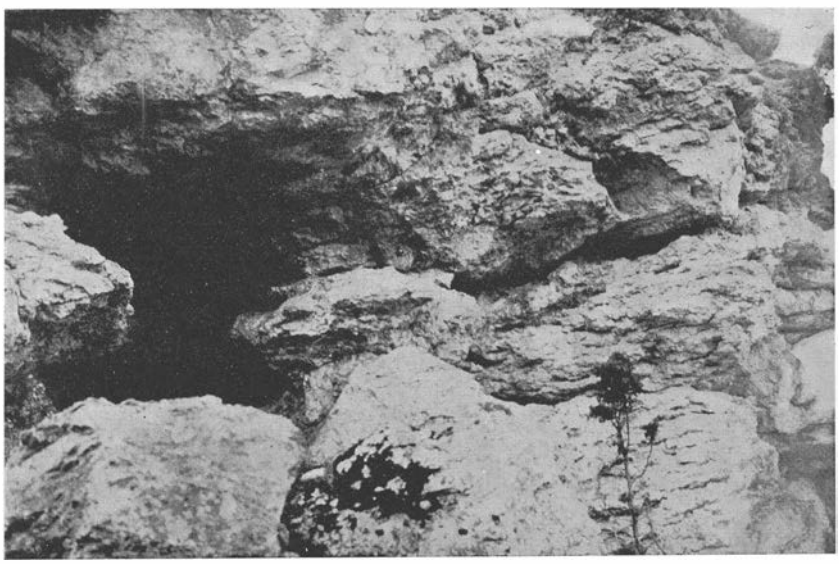


Fig. 59. Reef limestone with cave formed through marine abrasion in post-glacial time. Ire.

water we cannot draw any conclusions as to the sloping conditions of the bottom. But if we consider the variations of the rocks in connection with other circumstances. particularly the division of the reefs into definite belts in the direction NE—SW (map p. 11), a strike of the bottom beds in the direction NE—SW and a dip to the SE is more than probable.

It has been possible to map the reefs only to the extent of their exposure, and the picture of their distribution, number, size, etc. obtained from a sketch is on that account very incomplete. In spite of this a clear idea of their grouping along certain lines is gained, especially concerning the stages in which the reefs are most prominent, for instance the Slite stage. In this stage at least four such belts are distinguishable, running NE—SW and succeeding each other from NW to SE. The reef belts cannot be followed along the entire zone occupied by the stage, and we have therefore hardly any occasion to speak of barrier reefs, even if they run practically parallel to the shore. As a rule, too, individual lumps of a belt lie so

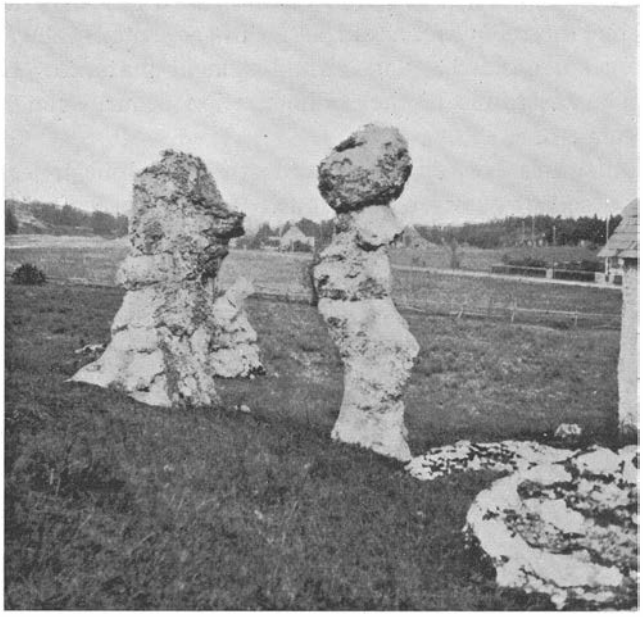


Fig. 60. »Raukar», stone pillars of reef limestone. Kyllaj.

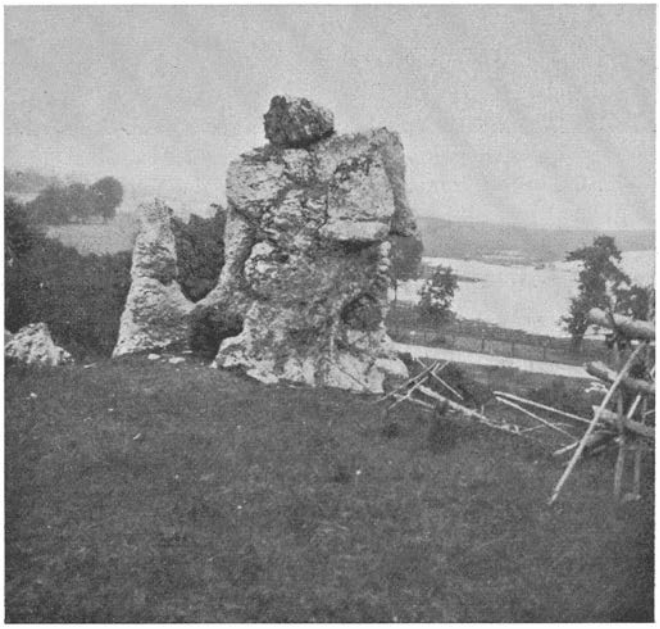


Fig. 61. »Raukar». Kyllaj.

wide apart that no connected »barrier» was formed. Nor is there any typical general lee-zone but the reefs are, as far as I can see, equally developed all around and often entirely surrounded by uniform fragment material. Locally, however, rather considerable variations in the sedimentation occur, even in the immediate vicinity of the reefs.

On diffuse transitions between reefs and stratified limestones the mapping of the reefs is of course not easily carried out. Where the reefs occur in a number

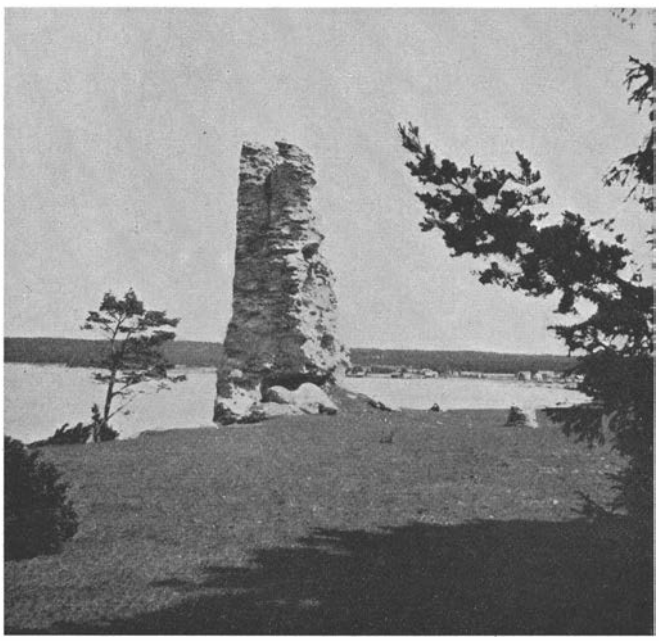


Fig. 62. »Jungfrun», a rauk 11.5 m high. Lickershamn.

of small lumps, as in the Hemse stage, the division into definite belts is not distinct, if it has existed at all. When a larger area of the sea-bottom has had a relatively horizontal position in the zone of development of the reef builders, the division of the reefs ought of course not to have followed the shore direction in detail, but the zone as a whole may nevertheless give an idea of this direction.

Destruction of the Reefs. — »Rauk» formation.

In the late Quaternary period Gotland was submerged in the basin of the Baltic. Beaches originating from the Ancylus and Litorina periods may be followed all over the island. The very conspicuous erosion phenomena met with in every

part of the island where the bedrock is exposed, originate from the same time. Abraded coast slopes are found not only on the recent shore but also in the interior of the country and at a varying height above the sea-level. In the slopes reef portions protrude as high cliffs, in the often vertical walls caves abraded by the sea appear (fig. 59) and close to the precipices remains of disappeared reefs stand in the form of isolated stone pillars. The forms in which the more or less disintegrated reefs appear are so typical that it is impossible not to notice them, and it seems to me as if a survey of the reefs of Gotland would be incomplete without a few words on erosion phenomena. (See also MUNTHE 1920 and 1921.)

On abrasion along a shore the loose rocks are of course the first victims of the destructive power of the waves. The harder or more compact ones will more and more form protruding rocks separated by bights and bays. In Gotland the large compact reef lumps stand for that reason like watch-towers in a winding wall built up of marly shales and bedded limestones. Where the reefs are less compact or are surrounded by limestones of the same tenacity as the reef limestone the abrasion slope obtained a more even course.

If the disintegration has proceeded so far that the stratified rocks surrounding a reef lump have become completely washed away there is usually not much left of the reef either, only scattered, particularly well cemented portions. These ruins of reefs are found as isolated stone pillars in the most varying forms (fig. 60—62) from the north to the south end of Gotland. They are called »raukar». Sometimes a solitary »rauk» is found, often of very considerable dimensions (fig. 62), but as a rule they occur several together, forming here and there whole »rauk» fields.

Typical »raukar» of stratified limestone are rarely met with, but sometimes, however, stratified limestone may be found together with the massive limestone.

LINNAEUS described and reproduced the »raukar» at Kyllaj, and those reproduced by him may still be found in the field. Some of the more important solitary »raukar» as well as the more beautiful »rauk» fields are now under the protection of the law.

Series of Strata and Reefs of Gotland in the Literature.

LINNAEUS, W. HISINGER and other scientists have visited Gotland and given notices of their geological observations. The first survey of the stratigraphy of the island was given by R. I. MURCHISON in 1847. Indeed MURCHISON got a good hold on the stratigraphical problems, that later on during nearly a century have tempted a lot of geologists to investigations in Gotland. When MURCHISON visited the island in 1845 (along with M. DE VERNEUIL) he had a close knowledge of the Silurian strata of England. The striking resemblance between the series of strata of Gotland and that of the English Wenlock and Ludlow districts was pointed out by MURCHISON, and the fossil lists he published (according to determinations by DE VERNEUIL and SOWERBY) give evidence of the fact that he has properly made out

the stratification. MURCHISON gives only scanty reports on the rocks but yet sufficient to show that he has observed also the reef limestones. He describes the series at Högklint, south of Visby, and points out (p. 19) that »the lowest beds consist of dark grey shales with nodules of limestone» and that »the next strata are reddish encrinital limestones». Later on in the account he says: »these beds graduate upwards into the uppermost mass, a hard grey limestone containing large irregular concretions, like the ball-stones of Wenlock and Dudley, which, as in England, descend into and apparently cut out the bedded rock».

No doubt MURCHISON here refers to the unstratified reef limestone with its bun-shaped stromatoporoids. His interpretation of the Högklint section shows this clearly. To judge from his description MURCHISON had not formed an opinion of the character of this limestone. In other parts of his work, however, he calls the equivalent formation (for instance at Visby) »coralline limestone» and when mentioning the »raukar» at Länna, north of Slite, reproduced already by LINNAEUS, he gives a somewhat more detailed interpretation of these rocks. »These rocks of Länna», MURCHISON writes (1847, p. 20), »are in fact dismantled portions of former hard coralline reefs, the earthy and softer portions of which have been worn and washed away». MURCHISON thus considered the massive limestone as reef limestone and he has especially pointed out its richness in corals. Still it would be wrong to say that he considered these reefs to be built up essentially by corals or in other words that by »coralline reefs» he meant coral reefs. Every time he mentions those formations in Gotland he points out their quality of »ball-stones». About the »raukar» at Länna he writes as a continuation of that quoted above: »The highest of these masses may be from thirty to forty feet high, and they consist of the small concretionary, coralline, marble-like limestone of pinkish and grey colours, each mass being, in fact, a huge ball-stone traversed by irregular lines of fracture.» When MURCHISON in 1839 in »The Silurian System» mentions the »ball-stones» in the Wenlock limestone (p. 210—212) he points out that they consist of concretions of varying size (the biggest ones with a diameter of 80 feet), at spots »abundantly charged with fossils, particularly corals».[1]

Through his investigations of the Cambro-Silurian of East Balticum FR. SCHMIDT had the best qualifications to judge also of the equivalent formations of Sweden. In his papers on the Silurian of Gotland (1859, 1890 and 1891) he takes on the whole the same view on the stratigraphical problems as MURCHISON, thus disagreeing with the interpretations given by G. LINDSTRÖM and W. DAMES. According to SCHMIDT the reef limestone consists in the cliffs of Visby essentially of coral limestone and

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[1] MURCHISON repeats the same description in his later works, e. g. in »Siluria», Fourth Edition, 1867. GRABAU has investigated the Wenlock ball-stones and equated them with ressembling formations at Clinton and Lockport in New York. He considers them to be real reefs, the English ones with corals as reef formers, the American ones with bryozoans (GRABAU 1913, p. 446). He uses the indication »ballstone reefs». See further CROSFIELD and JOHNSTON on p. 88.

crinoid limestone but in other places of stromatoporoid limestone. SCHMIDT, however, gives no analysis of the petrological character of the rocks.

G. LINDSTRÖM devoted four decenniums to the study of the Silurian of Gotland and he published a series of great and extremely valuable paleontological works on Gotland material. His efforts to explain the stratigraphical conditions are presented in small papers (1857, 1882 and 1888) and a few notices. But LINDSTRÖM and with him DAMES (1890) have not paid sufficient attention to the stratigraphical significance of the fossils. In some cases they have therefore made the mistake of letting the petrological character of the strata be decisive in the judgment of their stratigraphical position. »Crinoid and coral limestone» is to them not a local form of development but a stratigraphical horizon. The same thing applies to the »cephalopoda and stromatopora strata» etc. I have no reason to enter on an account or a criticism of these opinions. As to the rocks we find in LINDSTRÖM and DAMES no further particulars, but it appears from the statements given that the reef limestones belong to the part of the series called »cephalopoda and stromatopora limestone», which according to LINDSTRÖM forms the uppermost part of the Gotland series of strata, except at Hoburgen, where it is covered by crinoid limestone.[1]

W. DAMES made a journey to Gotland in the summer of 1890 and studied the stratigraphy of the island with LINDSTRÖM as a cicerone. The work he published in the same year is in many respects affected by LINDSTRÖM's opinions. In the cases when DAMES' opinion differs from that of LINDSTRÖM he expresses himself very modestly, »... glaube ich ein wenig anders auffassen zu dürfen, wenn ich mir auch nicht verhehle, dass es gewagt erscheint, auf Grund eines immerhin kurzen, wenn auch sehr lehrreichen Besuchs von der Auffassung des Gelehrten abzuweichen, welcher sich durch jahrelange eingehende Untersuchungen mit den kleinsten Einzelheiten der Geologie Gotlands vertraut gemacht hat.» (DAMES 1890, p. 1118.) We must grant, however, that DAMES is right in his opinion that the crinoid limestone and »stromatopora» limestone (the youngest divisions in LINDSTRÖM's scheme) are of about the same age, as the former not only underlies but also laterally surrounds and sometimes (as at Hoburgen) overlies the latter. About the deposition of these limestones DAMES says (p. 1122): »Die Crinoidenkalke sind, ... wohl so entstanden zu denken, dass der Meeresboden mit zahllosen Individuen dicht besetzt war, die nach dem Absterben in ihre einzelnen Stiel- und Kronenglieder zerfielen und so nach Verkittung durch Kalkabsätze feste Kalke bildeten, deren Mächtigkeit durch

[1] LINDSTRÖM (1888, p. 161) questions an inversion (!) at Hoburgen as an explanation of the fact that the crinoid limestone there covers the »stromatopora» limestone. DAMES (1890, p. 1118) objects to this explanation and considers that the crinoid limestone normally surrounds the other rock.

jüngere Generationen wuchs. ... Auf diesem Crinoiden-Meerboden siedelten sich nun an verschiedenen Stellen und zu verschiedenen Zeiten Stromatoporen an, welche allmählich Riffe von sehr verschiedener verticaler und horizontaler Ausdehnung aufbauten, ...» About the stromatoporoid limestone DAMES says further on (p. 1117): »Sie besteht meist aus undeutlich, oder gar nicht geschichteten Kalken, die zum Theil auf weite Strecken ganz aus Stromatoporen aufgebaut sind. Mit diesen zusammen erscheinen feinkörnige Mergel-Schichten und namentlich dichte Kalke ...»

As appears from the above, DAMES understood the great importance of the stromatoporoids for building up the Silurian reefs of Gotland and in a few words he also gave a good picture of the formation of the unstratified limestones as locally developed reefs.

G. HOLM (1901) accepted LINDSTRÖM's view of the stratigraphy. HOLM divides the Silurian of Gotland into two parts: »a lower division consisting of marlshales with nodules and beds of limestone and with sandstone and oolite at the top» and »an upper division consisting nearly exclusively of limestone, principally old coral reefs: accumulated masses of Corals, Bryozoa, Spongia(?), Echinodermata, etc.»[1] The following statement by HOLM is interesting [1]: »At the boundary between the two divisions conglomerates are not infrequent. The discordance as well as the occurrence at this horizon of a land animal, a scorpion, makes it probable that land existed in Gotland during the middle part of the Upper Silurian period.» As I previously pointed out there is a disconformity with a conglomerate of limestone in the Visby region, but it does not indicate a rise of the sediments above sea-level. It forms no doubt the boundary between two divisions of the Silurian but not in the way that HOLM presumed.

In 1892 the Geological Survey of Sweden began the investigation of Gotland and the commission was given to J. C. MOBERG. No one has been better qualified than MOBERG to make out the stratigraphy of Gotland and with energy he set to work. Already in 1905 the first map-sheet, »Hamra», could be printed on the scale of 1: 100000. Unfortunately MOBERG was then deprived of the task of continuing the survey. This was given to others with the explanation that the work must be hurried on. The result did not come up to expectation, the next map-sheet not appearing until 1921. At this time the investigation of the bedrock and the establishment of its stratigraphy had for some years past been undertaken by a pupil of MOBERG, J. E. HEDE, and through him the work has been carried on so that the last map-sheet was printed in 1940 (v. below).

MOBERG's survey includes only southernmost Gotland, but it has been funda-

[1] Quotation according to MUNTHE 1910, p. 1404.

mental for our idea of the stratigraphy in that part of the island. As his assistant served K. A. GRÖNWALL, who at the same time was investigating the Upper Silurian strata of Scania. Through MOBERG's and GRÖNWALL's works the age of the Silurian series of this part of Gotland could be definitely settled.

MOBERG himself did not publish anything about the results he had attained through his works in Gotland, but by H. MUNTHE (1902, 1907 and 1910) we have got to know about some of them. We do not obtain any further particulars of the construction and formation of the reefs from his mentioning them.

H. MUNTHE and H. HEDSTRÖM, both of them natives of Gotland, have devoted a lifelong work to the study of the geology of Gotland, the former in the first place to the Quaternary formations and to the Silurian of South Gotland, the latter to the Silurian of North Gotland. Their investigations chiefly find expression in the geological maps. Both, however, have taken a great interest in the stratigraphy as well as in the rocks, and they have paid special attention to the reef limestones too.

MUNTHE gives in 1902 a detailed description of the Silurian layers in a section at Lau. Then he also mentions the reefs of Gotland and quotes both WIMAN (1897) and SARLE (1901). MUNTHE (1902, p. 22) characterizes the reef limestone at Lau as an unstratified, partly somewhat marly, nodular limestone, which for the main part consists of stromatoporoids and corals. He points out that at the boundary between the stratified and unstratified parts the layers interfinger without any clear transition from reef limestone to stratified marl. He considers them to originate from the same time.

MUNTHE also investigated the rocks in the south part of Gotland, and he gave some brief informations about the reefs. As regards the reefs equivalent to the Sphaerocodium limestone (Hamra-limestone according to HEDE) he pointed out that they are marly and »relatively rich in *Corals* and *Stromatopora*, but nearly destitute of *Sphaerocodium*». (MUNTHE 1910, p. 1414.)

About the youngest limestones in southernmost Gotland, the crinoid limestone and the reef limestone, MUNTHE writes (1910, p. 1417): »The crinoid limestone sometimes shows a diagonal bedding on a small scale, and this may be interpreted as a shallow-water (but not as a true shore) phenomenon; more rarely pebbles are observed, and these may possibly indicate a temporary rise of the sea-floor, during the formation of the bed, to or above sea-level.» ... »The youngest bed» — called Ascoceras limestone — »is an unstratified compact and hard, somewhat clayey marble, reddish-brown or greenish-grey in colour. Unlike the crystalline Crinoid limestone it contains relatively large, coherent portions of *Crinoida*, which may well be preserved by reason of the great quantity of its marly material. The rock also contains greater or less colonies of *Stromatopora*. This youngest limestone, therefore, may be considered as a *Reef-limestone* formed chiefly of *Stromatopora* and of large fragments of *Crinoids* (principally roots and adjacent portions of the

stems) with marly sediments to fill the interspaces. The thickness may be estimated at about ten metres. While totally unstratified and built up of somewhat heterogeneous material the limestone bed has been especially suitable for the sculpturing of such irregular erosion forms as stone pillars ('raukar' in Gotland), caves, etc.»

The relation of the reef limestone (the Ascoceras limestone) to the crinoid limestone he describes as follows (1910, p. 1419): »In places it appears as if this rock» (the Ascoceras limestone) »were synchronous with the youngest parts of the Crinoid limestone, which in such cases may be considered as 'woods' of Crinoids living outside the Stromatopora and Crinoid societies of the neighbourhood and grown in situ in places where a sedimentation of marly material also took place. Probably, the Crinoid limestone was formed by masses of Crinoidal stems and arms which were accumulated outside the 'wood' whose roots in the marly sea-bottom gave rise to the *Ascoceras* limestone which is formed chiefly of the roots of the Crinoids.»

The varying petrological character of sediments deposited at the same time has especially interested MUNTHE and he gives much information about these cases. After a statement on rocks and fossils in the layers at Hoburgen he writes (1910, p. 1426): »This clear palaeontological and lithological difference between synchronous strata of adjacent districts may, most probably, be due to the sedimentation having taken place in belts at different distances from the series of Crinoid, Coral, Stromatopora and Bryozoan reefs which were growing at Hoburgen etc. during these times. The Crinoid limestone and the more marly limestones appear to have been deposited relatively near to the reefs, the harder and somewhat marly limestones at a little distance, and the Ilionia limestones proper,[1] farthest off.»

MUNTHE described the series of strata in many places and thereby tried to get possibilities of drawing a parallel between the strata in one place and those in another. That he saw the difficulties quite clearly is evident from his statement (1910, p. 1447): »I may say emphatically, that before we can completely understand the sequence of strata in Gotland, we must have much further help from the palaeontologists.» By his direction J. E. HEDE was engaged for the task in 1917, 20 years after another paleontologist, J. C. MOBERG, had to leave it.

HEDSTRÖM (1910, p. 1466) points out that also in the marls »here and there reef-forming corals and stromatopora are embedded; these increase in quantity towards the top [2] and are at certain spots heaped up into real small reefs». HEDSTRÖM also gives a good picture of the appearance of the crinoid limestone and the big reefs in northern Gotland, especially in the Visby region. He writes (1910, p. 1468): »Between 10 and about 13 m above the sea there rests a fairly coarse-crystalline yellowish-grey limestone, partly composed of Crinoid gravel and water-

[1] The Ilionia limestone is a brownish, somewhat bituminous limestone.

[2] Of the Upper Visby marl according to HEDE.

worn fossils, sometimes a real Crinoid limestone. In some of the coast sections this limestone is absent, but is always developed as soon as reef-formations appear at the same level, and is more distinctly marked with thicker limestone banks, the bigger and more numerous the reefs are. The layers on top of the reefs incline outwards from there while the layers below the reefs dip down under them. This stratum is in many instances very good to serve as a guiding and indicating stratum ...» HEDSTRÖM stated that in the vicinity of Visby the reefs occupy a considerable part of the series of strata, often most of horizon III (= the Högklint stage), and he adds (p. 1474): »In the vicinity of Visby ... in the parishes of Lummelunda and Stenkyrka the reefs are very much smaller, forming the steep, small cliffs prominent in the coast sections, whilst the outlines of the coast in the stratified layers lying between the reefs are cut in the form of an arch towards the land.»

»The reefs are composed of non-stratified accumulations of chiefly *Stromatoporae*, in addition to which there occur, but less plentifully, some corals of the genera *Halysites*, *Heliolites*, *Favosites* etc., as well as some Bryozoaries etc. The marl nests occurring in the reefs are frequently paying lodes for fossils. Here one may thus find Crinoid crowns, Gastropoda, Brachiopoda etc.»

»The reefs can show a lot of particularly beautiful erosion phenomena. Almost exclusively confined to the reefs are the 'raukar' or stone giants characteristic of Gothland, wherefore the reef-limestone has also been called 'rauk'-limestone; furthermore the numerous cave formations are situated mostly in the reef-horizon.»

HEDSTRÖM gives some more informations about the reef at Korpklint and its substratum of crinoid limestone and marl. As to the stratified rocks formed at the same time as and around the reef he stated the following (p. 1476): »The lower part of the reef is thus equivalent to the Crinoid limestone nearest to the reef, further away from the reef there occur fine to dense, flakey limestones and finally marl-shales with limestone-seams. The middle and upper parts of the reefs are replaced by conglomerate-like and oolitic limestones, or by bituminous limestone and marl-layers ...»

In 1910, when the guides written by MUNTHE and HEDSTRÖM for the excursions to Gotland of the XIth international geological congress were being printed, the Swedish geologists received a large work on the stratigraphy of Gotland written by the Dutchman E. C. N. VAN HOEPEN. It appeared as a complete surprise. None of the Swedish geologists had heard about VAN HOEPEN, not even those who like MUNTHE and HEDSTRÖM had been mapping on the island at the same time as he had been there.

VAN HOEPEN's work is worth recognition, particularly if we consider that the result has been attained after less than four month's studies in the field. Nobody had earlier tried to make out the stratigraphy through such comprehensive studies. The result was that VAN HOEPEN largely agreed with MURCHISON's and FR. SCHMIDT's ideas on a constant dip towards SE and the appearance of the different stages in

SW—NE belts with the oldest strata in NW, the youngest in SE and S. I have no reason to give an account of VAN HOEPEN's stratigraphical scheme here, and still less to compare his interpretations of the geological conditions with the results that have come out through HEDE's more comprehensive, more profound and more careful investigations, going on for more than 20 years. I shall, however, quote the substance of VAN HOEPEN's statement on the reef limestones.

The lowest great reefs are called by VAN HOEPEN the Korpklint limestone, and the crinoid limestones surrounding it are called the Högklint limestone. (HEDE brings them and other sediments deposited at the same time together in the Högklint group.) VAN HOEPEN wrote of the Korpklint limestone (1910, p. 95), that it is built up chiefly of zoogenic material. *Stromatoporoidea, Halysites, Favosites* and *Heliolites* form the main part, but other corals, crinoids, and brachiopods appear abundantly too. Fine marl, rich in well preserved fossils, appears in primary cavities inside the reefs, and around these banks of conglomeratic limestone with fragments of stromatoporoids, corals, etc. have been deposited. There is often no sharp margin between the reef limestone and this fragment limestone. About other reefs VAN HOEPEN spoke less in detail but he stated that stromatoporoids and corals were always the reef formers proper.

C. WIMAN published in 1897 his paper »Über silurische Korallenriffe in Gotland». He pointed out the character of the unstratified lumps of limestone emerging from the cliffs in northwestern Gotland, he illustrated their building and appearance and tried to show how they have been formed.

WIMAN's view on the formation of the reefs and their general character has attracted attention but little approval by those who have had occasion to study the Gotland reefs on the spot. »Ein Korallenriff», WIMAN writes (p. 313), »ist ein isoliertes, über den Meeresboden sich erhebendes Kalklager, wesentlich dadurch gebildet, dass die ästigen Korallen und das lückenreiche Gefüge des Korallenriffes den Kalkdetritus oder den Kalksand auffangen und verhindern, dass er sich über den Meeresboden *gleichmässig* ausbreite.» He continues (p. 316): »In runder Summe besteht etwa die Hälfte des Riffgesteins aus Korallstöcken. Die andere Hälfte besteht aus dem Kericht des Riffes, dem organogenen Kalksand, zu welchem die ganze reiche korallophile Fauna, in so weit sie Kalkbildungen besitzt, ihren Beitrag geliefert hat.» The statements quoted appear in such a way that the reader gets the idea that they are based on WIMAN's own investigations of the reefs of Gotland, though they are only reports of WALTHER's accounts of recent coral reefs (WALTHER 1893/94). WIMAN himself calls attention to the fact that in the Gotland reefs »die resp. Korallstöcke jeder für sich im Allgemeinen wenig dazu geeignet gewesen sind, den Kalksand festzuhalten» (p. 317). Therefore the corals in the Gotland reefs did not conform to his idea of good reef formers. WIMAN writes of these (p. 317): »Je mehr verzweigt eine Koralle ist, einen um so besseren Riffbilder giebt sie ab, desto mehr Kalksand vermag sie aufzufangen.» He adds to show that

there are parallels to the Gotland reefs among the recent coral reefs: »Aber es finden sich auch in der Gegenwart Korallenriffe, in deren Aufbau massive und weniger verästelte Formen eine wichtige Rolle spielen. Und es sind ja auch nicht nur die verzweigten Korallen, sondern auch die Tausende von Höhlen und Schlupfwinkel der ganzen Ansiedelung des Riffes, welche den Kalksand festhalten.»

One gets no clear idea of the construction of the Gotland reefs from WIMAN's work. Apart from the above-mentioned negative statement that the branched corals do not play an important part in the Gotland reefs and the positive, but somewhat vague information, that in them you find especially more massive corals (p. 318), you learn nothing of the reef formers proper. Bryozoans appear but they are »an und für sich als schlechte Riffbilder zu betrachten» (p. 317). WIMAN does not mention anything of the way in which stromatoporoids and calcareous algae have taken part in the formation or how they appear in the reefs. He speaks very carefully on this question (p. 318): »In Gesellschaft mit den mehr massiven Korallen, welche man im Riffgestein vorzugsweise findet, kommen auch Massen gewaltiger Stromatoporen und Kalkalgen vor.» About these WIMAN writes (p. 318): »Diese sind jedoch vielleicht nicht als eigentliche Riffbilder zu deuten. Wenigstens haben sie, in so fern ich habe beobachten können, nicht allein Riffe erzeugen können, obschon die Kalkalgen 50 % und mehr der ganzen Gesteinsmasse ausmachen können, z. B. in einem etwa einen halben Meter mächtigen Lager am Pulverkeller, N von Wisby . . .» It is to be noticed that the calcareous algae WIMAN refers to do not occur within the reefs but in younger bedded limestones. We are not told anything of their occurrence in the reefs of Gotland and the same is the case concerning the stromatoporoids. Even these latter occur in the stratified rocks, and as a rule they are better preserved there (less recrystallized) and catch one's eyes more than in the reefs.

I regret that this somewhat detailed review of WIMAN's idea of the building of the Gotland reefs has to be a criticism on certain points. It has to be made clear, however, that WIMAN's widely distributed work does not give any support to an idea contrary to that vindicated by DAMES, and later on by VAN HOEPEN, HEDSTRÖM, MUNTHE, HEDE and the author. All those mentioned and other geologists too have seen and understood the important part the stromatoporoids play in the Gotland reefs. WIMAN has wholly ignored the stromatoporoids, and he has also avoided giving a further account of the real importance of the corals and of their part in the reef-formation. He has omitted to show if calcareous algae, bryozoans and other organisms have actively cooperated in forming the reefs or else have been of significance to their formation. Indeed WIMAN seems not only in his general reasoning but also in his description of special conditions to be highly dependent on WALTHER's investigations of recent coral reefs.

Thus WIMAN's investigation has not contributed to make clear the origin of the compact frame of the Gotland reefs. As we shall see he has not given us a good idea of the other constituent of the reefs, the matrix, either. About this he writes (p. 318): »Das zweite Element, woraus das Riffgestein besteht, ist der Kalksand.

Ein grosser Teil der Kalksteine Gotlands besteht aus Kalksand, dessen Entstehung nicht mit der Bildung von Riffen in Verbindung gestellt werden kann. Er ist also ganz einfach ein zoogenes Sedimentationsmaterial, welches überall entstehen kann, wo Kalkorganismen in genügender Menge vorhanden sind und wo die Zerkleinerung der Kalkausscheidungen vorsichgehen kann.» It ought to be observed that only in the first quoted sentence does WIMAN speak of the reefs, in the following quite generally of calcareous sand in the Gotland limestones. We do not learn if he considered the calcareous sand also in the reefs to be deposited without connection with the reef formation.

WIMAN writes further on (p. 318): »An Material zur Bildung von Kalksand mangelte es nicht in der an allen möglichen kalkausscheidenden Organismen so reichen obersilurischen Fauna.» But he finds it difficult to explain the disintegration of the material into calcareous sand. He tells us about the activity of different animals in this direction (mainly according to WALTHER) but says he has found no traces of such an activity in Gotland. Nor does a mechanical wearing seem to be an acceptable explanation. He says about that (p. 319): »Losgebrochene Korallenstöcke können von der Brandung hin und her auf dem Riff gerollt werden und Schalen zermahlen, keine grössere Bedeutung aber kann man dieser Entstehungsweise von Kalksand zuschreiben.» He continues, and it is to be observed that he now again speaks of the conditions in the reefs: »Man muss also, was die gotländischen Riffe betrifft, einen neuen Faktor suchen, um die Entstehung des Kalksandes zu erklären und ein solcher bietet sich von selbst in den unzähligen Enkrinitkalken dar.» It is right as WIMAN says, »dass die Krinoideen von selbst in ihre Kalkelemente zerfallen» and that they can form a calcareous sand or a calcareous conglomerate even without intervention of »bohrender und zerbeissender Organismen». But it is not right to see in this the factor that explains the deposition of the matrix of the reefs. It is true that crinoid fragments are found abundantly in the Gotland reefs, but still they are remarkably little represented if we consider that as a rule they wholly fill the bedded limestones surrounding the reefs. Fragments of other organisms and organic silt usually play a more important part in the reef matrix.

In another paper (1933) WIMAN has treated the reefs of Stora Karlsö. I have already previously (p. 29) spoken of this work, which is of interest on account of the attempt to reconstruct the reef-massif and the progress of its growth. WIMAN thought he could fix (p. 282) »dass *Thecia swindernana* GOLDF. die Struktur des Riffkalkes bestimmt und einen grossen Teil des harten Kalksteins aufgebaut hat». Besides *Thecia* WIMAN has observed in the reefs other corals, bryozoans and representatives for the coralline fauna usually occurring in the reefs. The stromatoporoids, which play an important part also in these reefs and which affect the structure of the rock in a higher degree than the corals, have been wholly overlooked. As it appears from the above (p. 52, see also fig. 45—46) the parallel structure can be rather well developed by lamellar reef formers (stromatoporoids and corals) and

thin interstratifications of marl. The latter sometimes form real strata dividing the limestone into thick beds.

M. C. Crosfield and M. S. Johnston (1914) have studied the *ballstone* of Shropshire and given us a description of this rock. They have shown that on the whole it is of the same character as the reef limestone in Gotland. They indicate the difference between the rocks as follows (p. 214): »The differences between the reefs of Gotland and *ballstone* appeared to be due, not to any inherent differences, but to be the result of the longer continuance in time of the reef-phase in Gotland, which has introduced a greater variety into the fauna of the reefs, and also into the lithology and faunas of the associated beds, both at the base of and surrounding the reefs.»

Crosfield and Johnston give us also a clear and comprehensive comparison between the *ballstone* and other Silurian reef limestones. They quote numerous works by a great many authors and discuss different questions concerning the reefs. It is a pleasure to me to refer to their paper. Crosfield and Johnston recommend (p. 223) »the ancient and useful term 'coral-reef' to indicate certain types of rock structure of considerable size formed by attached coral colonies in Palaeozoic seas». Contrary to A. J. Jukes-Browne they do not seem, however, to object to the use of the indication in a much wider sense. As appears from the preceding the author approves of Jukes-Browne's views (p. 14): »... it is clear that the mere abundance of corals in a Palaeozoic limestone is no proof that such a limestone formed part of an ancient coral-reef. Yet it has often been asserted that certain masses of limestone are coral-reefs, merely because they are *coralliferous* limestones.»

»Note on some reef-structures in Gotland» by F. A. Bather (1914) is appended to the paper of Crosfield and Johnston. Bather shows in two sketches the relation between the reefs and surrounding limestones.

W. H. Twenhofel (1916) has made many good observations on the Gotland reefs. About the reef builders for instance he writes (p. 347): »The organisms which played the greatest part in the development of the reefs belong to the Stromatoporoidea, and there are probably a half score of these for every colony of all the others put together.»

As regards the relation between the reefs and surrounding stratified rocks he is of another opinion than the author. Twenhofel writes (p. 350): »the coralline rocks should be correlated with strata holding a much lower level». He thus presumes that the surface of the reefs has lain considerably higher than the surrounding sea-bottom. He draws the reefs as calcareous bodies with wide base and narrower upper part (fig. 1, p. 351), and it is natural that with such a form they have been able to stand upright even if the ground has been marl and other loose sediments.

As has been shown in the preceding the reefs have often the form of a cone placed on its apex, and still oftener they have a strongly extended upper part, and it would be out of the question that these reefs should avoid turning over if they had not been supported by sediments accumulated on their sides. The flanks of the reef have also in many places grown directly on crinoidal fragments and other loose sediments surrounding the reef, and the surface of these sediments cannot therefore have been lying much lower than the surface of the reef (cf. p. 56). Faunal correspondences between argillaceous fillings in the upper parts of the reefs and deeper lying stratified sediments may be due to the great changes of the fauna according to the milieu. The character of the bottom can, within certain limits, have been of more importance for the development of a species than the time. TWENHOFEL is not unacquainted with these views when he writes: »These varied conditions upon, within, and about a coral reef will be and are reflected in the faunas of the bottom, each species selecting that bottom and those conditions on and under which it best thrives . . .»

WEDEKIND and TRIPP (1930) have in a short paper treated the Gotland reefs. They call them coral reefs and characterize them as barrier reefs or »Sammelriffe». They have observed that the reefs occur in great numbers and are accessible in innumerable sections, they write: »es gibt wohl kaum ein bekanntes Gebiet auf der Erde, das für das Studium der Entstehung fossiler Barrierriffe geeigneter wäre als Gotland», and they add (p. 297): »es ist merkwürdigerweise noch kein Geologe dazu gekommen, das Problem der Korallenriffenentstehung in Betracht zu ziehen».

The positive results as regards the reef formation which WEDEKIND and TRIPP think they have come to, they comprehend in two points: »1. Die Korallenriffenentwicklung ist abhängig vom Verhältnis des Wachstumsimpulses der Riffbildner zum Impuls der Sedimentation. 2. Die Korallenriffe Gotlands . . . entwickelten sich in der Übergangszeit von einer terrigenen Phase zu einer thallasigenen . . .» The first point we can pass by as it only proves the self-evident fact that a reef rises among stratified sediments if in any place the development of reef-forming organisms is stronger than the deposition of stratified sediments. The second point says that the Gotland reefs have been formed during transgressions. As appears from the present investigation the reefs could just as well have been formed during regressions, and we have a clear example of that in the reefs of the Högklint stage, which have been formed during the transition from the Visby marl deposited in deeper water into the Tofta limestone deposited in very shallow water.

Concerning the reef formers WEDEKIND and TRIPP say (p. 299): »In mannigfaltigster Vermischung sind Korallen, Brachiopoden, Crinoiden, Stromatoporen, Bryozoen in den Sammelriffen anzutreffen. Manchmal haben die Stromatoporen die Majorität in der Riffauna, dann sind es wieder einmal die Crinoiden oder die Korallen, die vorherrschen.» In spite of this on the whole correct observation WEDEKIND and TRIPP speak only of »Korallenriffe» and of corals building up the

reefs. Their idea of a reef also seems peculiar when among different types they have as the first the turnip reefs, which they characterize as follows (p. 299): »*Das Rübenriff.* Es ist ein Feld von dicht nebeneinander wachsenden Einzelkorallen.» It is possible that an argillaceous sea-bottom closely set with cup corals could have a certain resemblance to a turnip-field, but to call such a formation a coral reef will hardly gain agreement from any quarter. There is no reason to discuss the paleogeographic and stratigraphic ideas of WEDEKIND and TRIPP.

I will finish my summary of the literature on the Silurian of Gotland and especially on the reefs by illustrating J. E. HEDE's works with the utmost brevity. No geologist has had nearly the knowledge of the rocks of Gotland that HEDE has. With extraordinary care and a never failing interest he has prosecuted his work.

In a couple of works (1921 and 1925) HEDE has given a short survey on the Silurian of Gotland and in some papers he has discussed special stratigraphical questions. But it is in the geological maps and their descriptions he has principally put forward the results of his investigations. It is impossible and inconvenient to review HEDE's works here, but to show their general content and their richness in detailed reports I shall quote some select statements about reef limestones of the Högklint stage and rocks surrounding them.[1]

Of the Högklint limestone in northern Gotland (maps Visby and Lummelunda) HEDE writes (1940, p. 18): »The Högklint limestone, the lithological development of which varies much, is built up of stratified rocks, limestones, and marlstones, as well as of reef limestone equivalent to those. Of these two components — the stratified and unstratified — the former constitutes the chief bulk of the series, while the latter, appearing in the form of bigger or smaller swellings (reefs) inside the stratified component and at different horizons, forms a smaller but yet considerable part of it. Here and there portions of indistinctly stratified, reef-like limestone occur too. This rock, which can be said to be an intermediate form between the two components just mentioned, only plays an subordinate part in the building of the series.»

»Also the paleontological development varies considerably. Both kinds of change in facies make themselves known in a horizontal as well as a vertical direction and not only within different districts but often also at adjacent places. The kind and degree of these variations will appear more plainly from the following statement of the building of the series, the fossil content, etc. — The maximum thickness of the Högklint limestone amounts to about 35 m.»

»At the places where reefs occur within the lower part of the Högklint limestone the basal part of the stratified component consists of a distinctly stratified, hard, crystalline limestone, thin-bedded to thick-bedded, light grey to yellowish or

[1] This paper on Gotland reefs was ready for printing already in 1938, and the author had then quoted HEDE's earlier works. If possible the author has exchanged this for HEDE's last statements of 1940.

brownish light grey, in places faintly greenish light grey and sometimes ruddy. The beds, the thickness of which does not seldom amount to 1 m or more, are sometimes separated by very thin, greenish, highly marly layers.»

»This limestone is as a rule very rich in crinoids, and to a great extent almost exclusively made up of these (crinoid limestone). The fauna of the limestone further contains stromatoporoids, corals (»*Lindströmia*» *dalmani, Polyorophe glabra,* forms of *Heliolites* and *Favosites, Halysites catenulatus,* etc.), bryozoans, brachiopods (i. a. *Dictyonella capewelli, Platystrophia* sp., *Linoporella punctata, Parmorthis basalis, Bilobites verneuilanus, Plectodonta* cf. *duvali, Schuchertella pecten, Rhynchotreta cuneata, Camarotoechia borealis, Atrypa reticularis,* and *Atrypina angelini*), gastropods, tentaculites, trilobites, ostracods, etc., of which animal groups the four first mentioned, at least in places, are found rather richly, the others only sparsely. The flora is represented by *Solenopora gotlandica,* which is here and there rather common.» — Then a detailed fossil list follows.

»This crinoid limestone forms the substratum of the reefs, and it also surrounds greater or smaller parts of them on the sides. Its thickness, which varies much, may reach maximally about 15 m. The boundary between this limestone and the underlying Upper Visby marl is very strongly marked.»

»Already at a relatively short distance from the reefs the limestone now described grades laterally into more marly and more thin-bedded sediments, and within the areas between the different reefs the lowest part of the Högklint limestone is chiefly built up of such ones. This transition, which takes place rather rapidly, appears in this way: the limestone gradually becomes more and more marly and poorer in crinoid fragments and loses its character of crinoid limestone, at the same time as the rock, on the whole at least, gets richer in other fossils and more thin-bedded.»

»At a greater distance from the reefs the member in question consists of a thin-bedded limestone (the thickness of the beds varies between 1 or 2 and 8 cm), grey or bluish grey, when weathered light brownish grey, dense to fine-crystalline, more or less marly, interbedded with thin (up to 3 cm thick) beds of bluish grey marl. The limestone is sometimes slightly arenaceous. The stratification planes of the limestone beds are not seldom uneven and nodular. The rock is as a rule highly fossiliferous.» — The thickness amounts to about 10 m but is usually less. — Fossil list adjoined.

»The uppermost parts of the stratified series of the Högklint limestone are to a large extent composed of thin-bedded (in even flakes), sometimes thick-bedded limestone, light grey or faintly brownish light grey, often greyish white, when unweathered faintly bluish light grey, almost dense to fine-crystalline, mostly finely oolitic or oolite-like. Sporadically this limestone encloses small, irregular, occasionally lenticular, reef-like portions of nearly dense limestone, rich in stromatoporoids.»

»The fossil content of the limestone in question is characterized in the first place by a great abundance of calcareous algae, among others »*Spongiostroma*»

holmi, Hedströmia halimedoidea, Solenopora cf. *compacta,* and *S. gotlandica,* mostly sparingly occurring, and small, not yet more closely determined forms, abundantly met with. The oolite-like structure of the rock seems to be chiefly due to the last-mentioned small calcareous algae. Further there are found stromatoporoids (mostly small forms), and bryozoans, as a rule numerously. In places crinoid fragments are also common. Besides there occur sparsely corals, brachiopods (*Trimerella* sp., *Camarotoechia* of *nucula*-type, *Eatonia*? sp., and small forms with smooth shells), and gastropods (*Tryblidium unguis, »Pleurotomaria» limata, Poleumita discors,* etc.).» — The thickness is at most 5 m.

»The limestone now mentioned grades laterally into and is in places overlain by thin-bedded, more seldom thick-bedded limestone, light grey to brownish grey (sometimes faintly greenish light grey and occasionally a little lilac), dense to very fine-crystalline, often extremely fine-oolitic, sporadically very hard and with a flinty fracture. Small stylolites are rather common. The limestone beds are not seldom separated by thin, greenish, highly marly laminae. In some places alternation between this limestone and the just mentioned oolite-like limestone has been observed.»

»The limestone in question is as a rule rich in stromatoporoids, and in places these fossils occur so numerously that the rock is made up chiefly of them. Then the rock is usually indistinctly stratified and reef-like. The fauna further consists of mostly very sparingly occurring corals, crinoids, bryozoans (in some places still rather commonly), brachiopods (mainly small forms with smooth shells), and gastropods. Besides *Leperditia* sp. is found, here and there rather abundantly. The flora of the limestone is represented by i. a. »*Spongiostroma» holmi* and *Solenopora gotlandica,* the former occurring fairly commonly as mostly small specimens, the latter as a rule sparingly. — In some limestone beds the fossils are rolled by waves and strongly worn. The rock in these beds often shows a conglomeratic structure.»

»As is also evident from what has been already mentioned, the Högklint limestone is made up not only of stratified sediments but also of reef limestone. The latter appears as larger or smaller swellings, reefs, of very irregular and varying shape. The reef limestone occupies different horizons in the series. Thus some reefs extend vertically through most of the series, while others have only a less extent in that direction. In correspondence to this the thickness varies rather considerably too. Most reefs may reach a maximum thickness of only some few metres, while others are occasionally up to about 30 m thick. Also the horizontal extent varies greatly. Most reefs may reach only a few tens of metres, but several stretch one or two hundred metres, and single ones nearly 1 km laterally.»

»The reef limestone is usually light grey or greenish light grey but not seldom brownish light grey and sometimes faintly bluish grey. It is generally dense or nearly so and more or less marly. Small druses with calcite crystals are fairly common. Small parts or »nests» of greenish marl occur here and there. Sometimes greater or smaller parts of stratified limestone (as a rule crinoid limestone) are found embedded in the reef limestone. The rock is particularly rich in stromato-

poroids, and to a great extent it consists chiefly of representatives of this animal group. As a rule corals (especially tabulate ones), crinoids, and bryozoans are also very important constituents in the fauna of the reef limestone. Besides there occur i. a. brachiopods (*Platystrophia* sp., *Parmorthis basalis, Rhipidomella hybrida, Bilobites verneuilanus, Leptaena rhomboidalis, Rhynchotreta cuneata, Camarotoechia borealis, Atrypa imbricata, A. reticularis, Spirifer* spp., small forms with smooth shells, etc.), gastropods, cephalopods, and trilobites, at most only sparingly but in more marly parts of the rock rather abundantly.» — Fossil list adjoined.

»Locally the Högklint limestone shows a facies which at least partly differs much from the forms of development described in the above.» Thus the Högklint limestone consists in places of »i. a. red, grey, and black marl shales, more or less bituminous, and grey, bituminous limestones». This is the »Pterygotus-layer».

REEF LIMESTONE IN UPPER ORDOVICIAN AND LOWER SILURIAN.

»Leptaena Limestone».

The Ordovician series of strata is well developed in Sweden. It has also a very large extent in the Scandinavian peninsula. The rocks are of different kinds, but shales and bedded limestones are completely predominant. Coarser sediments, sandstones and conglomerates are rare. The series of strata is thoroughly marine.

Fossils are common. In the limestones trilobites and cephalopods are good index fossils, in the shales graptolites and brachiopods. Cystoids and crinoids are numerous in certain formations, lamellibranchs in others.

Reef-building organisms are found to a very limited extent and proper reefs occur in the Ordovician of Sweden only within the Cambro-Silurian field of Dalecarlia. Those reefs which have in literature usually been mentioned as *Leptaena limestone* are found in Upper Ordovician and extend up into the lower part of the Silurian series of strata.

The reefs appear in two different horizons, the lower mainly within the Chasmops stage, the upper within the Trinucleus and Dalmanites stages. As WARBURG (1925) and ISBERG (1934) have shown, they are faunistically different. By THORSLUND's works (1935 and 1936) the stratigraphical position of the Leptaena limestone has been made clear further. The lower Leptaena limestone, the *Kullsberg limestone*, never reaches below the Chasmops limestone and never above the black Trinucleus shale. The upper Leptaena limestone, the *Boda limestone*, appears between the black Trinucleus shale and the Rastrites shale. In its middle part THORSLUND has observed sandy layers. He fixes the limit between Ordovician and Silurian to these strata.[1] The reefs lie scattered within the Paleozoic sedimentary district north of Lake Siljan, and the development is largely seen to be everywhere homogeneous, even if petrographical variations are to be found.

[1] The strata are usually tilted or else in a strongly dislocated position. The stratigraphical conditions and the position of the Leptaena limestone in the series of strata were on that account not disentangled for a long time. TÖRNQUIST, v. SCHMALENSEE, STOLPE, and NATHORST have in several works set forth different views on the stratigraphical problems of the Leptaena limestone. I have no reason to review these works here, as they do not contribute to the understanding of the questions of sedimentary petrology.

The Character, Form, and Size of the Reefs.

The Leptaena limestone is massive; it has in other words a typical reef structure. Changes into stratified limestones can be traced however in many places, and the Leptaena limestone thus does not differ in this respect from other reef limestones, e. g. the Gotland ones. Brecciated portions are common and also the dense matrix often shows sharp fragments (fig. 67 and 68). Conglomerates with plainly corroded balls are known (fig. 69).



Fig. 63. Reef limestone, typically splintery. — Osmundsberget.

The Leptaena limestone is usually dense, hard and very splintery (fig. 63). The colour is most often light, white or faintly red, but not seldom it shows stronger colours: red, green or black brown.

The reefs of the Leptaena limestone are formed as lenses or nodules (fig. 65), sometimes flatly extended, sometimes more spherical. Irregularities in form, however, are found everywhere.

The size of the reefs varies. But we know only slightly the smaller reefs, as they are not outcropping and have only casually been exposed (e. g. at road works). The larger reefs sometimes have an extension of more than 1000 m. In many cases they now rise as hills or ridges above the surroundings. As they contain a technically valuable limestone they have been made the object of intense quarrying, which in a high degree has made the study of them easier (fig. 64).



Fig. 64. Quarry in reef limestone. — Kallholn, 1940.

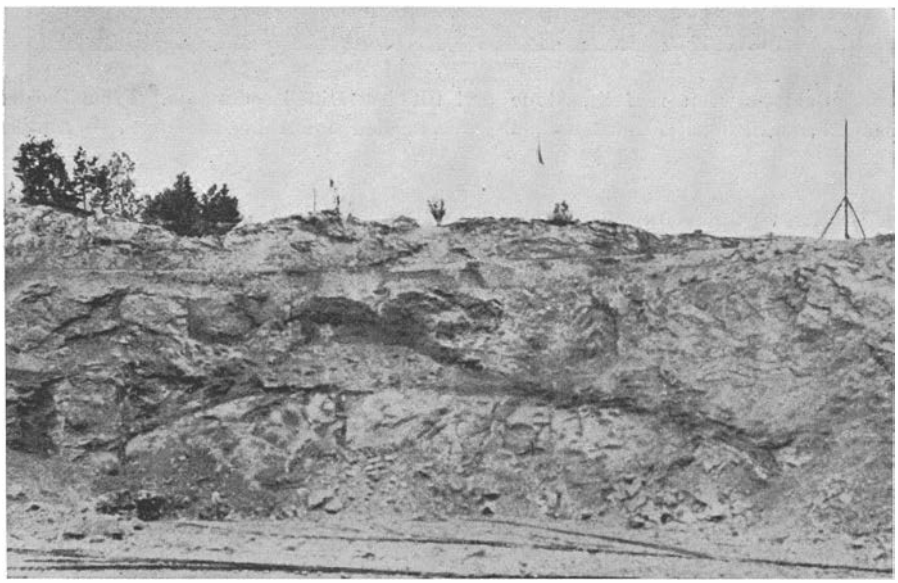

Fig. 65. Lens of reef limestone in stratified rock. — Kullsberg.

The relation of the reef limestone to the stratified rocks.

The relation of the reefs to surrounding stratified rocks was long unclear and a subject of discussion. Already in 1909 the author made studies in the quarries existing at that time, and three years later he visited some of them again. He was on that occasion accompanied by O. Isberg, who later on continued the investiga-



Fig. 66. Contact between reef limestone and tilted stratified sediments. From the left: reef limestone, marl, black Trinucleus shale, thin-bedded limestone, and marl. — Amtjärn.

tion, in the first place concerning the relation of the reefs to surrounding stratified sediments. The results of his work were published in 1917. Isberg's paper gave valuable information about the contacts of the Leptaena limestone and by that contributed to the solution of the age of the limestone. Thorslund gave (1935 and 1936) a more detailed account of the occurrence of the limestone and new details as regards the connection between reef and stratified sediments. In just a few words the conditions of two reefs will be mentioned here as an example, viz. the reefs at Amtjärn and at Kullsberg, which the author has on several occasions had an opportunity of studying.

The reef of Amtjärn is lenticular and has a length of about 400 m. and a thickness of about 30 m. The reef lies in vertically tilted layers (fig. 66) but the mutual position of these is little displaced. The stratigraphical conditions are relatively clear. The reef is underlain by stratified Chasmops limestone, normally

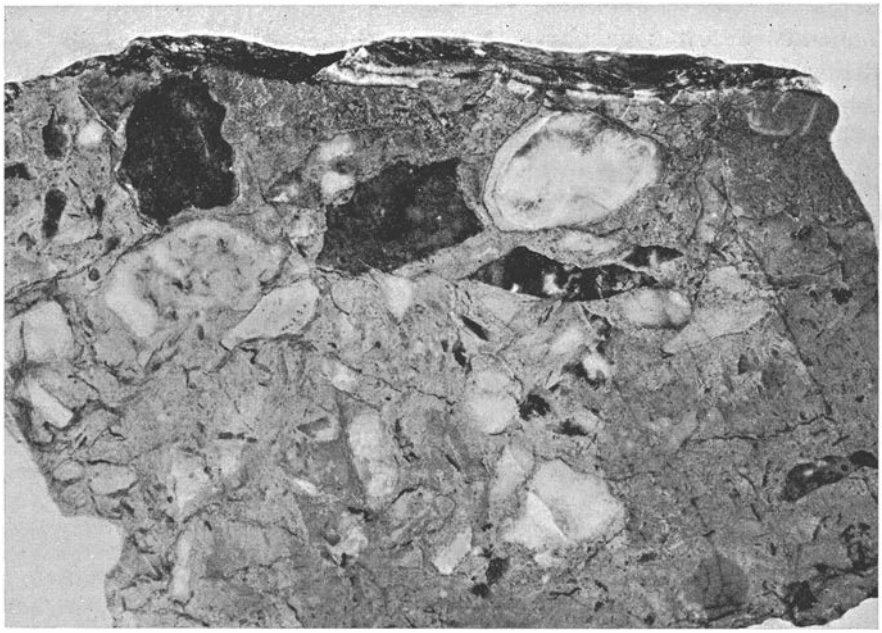

Fig. 67. Reef limestone, marly portion with fragments of the reef. Kallholn. (Pl. 1209.) — 1/1.

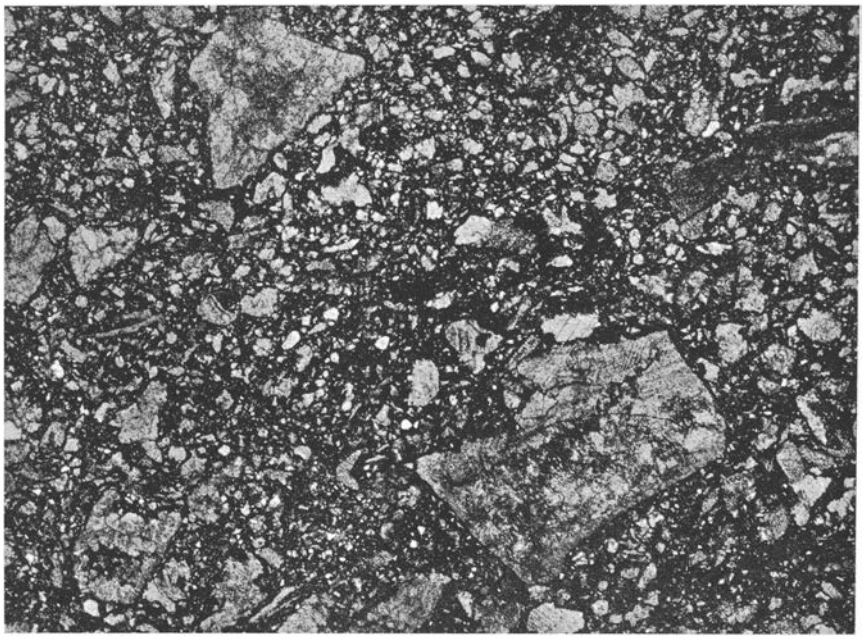

Fig. 68. Sandy matrix in reef limestone. Kallholn. (Pr. 4722, Pl. 1197.) — 10 ×.

developed as fragment limestone, and it is overlapped by marly strata with thin limestone beds, followed by black Trinucleus shale. Against its borders the reef is divided into several out-thinning beds interbedded with fragment limestone and marly layers.

At *Kullsberg* the stratigraphical and tectonic conditions are more complicated. In the large quarry, originally made in reef limestone, stratified limestones are now principally to be seen. A smaller reef lense was still exposed in the lower



Fig. 69. Conglomeratic reef limestone. — Osmundsberget.

part of the series in 1940 (fig. 65). It was wholly surrounded by fragment limestone and marl, both rich in crinoids and other pelmatozoans. Some metres higher up in the series of strata another bigger reef lay, now almost entirely quarried away. This reef was, like the above-mentioned reef of Amtjärn, at its borders divided into beds, which ran into stratified fragment limestone belonging to the Chasmops stage. — At the entrance of the quarry at Kullsberg are seen the remains of a reef, which is strongly broken, tilted and pressed over a younger stratified sedimentary series. In this THORSLUND has identified Trinucleus, Dalmanites and Rastrites shale. In this place too the reef limestone has been enclosed by marly, thin-bedded layers, rich in crinoids.

The conditions at Kullsberg show that within the same relatively restricted series of strata several close-lying reef lenses of varying size have been developed. As in the Gotland Silurian series, the Ordovician reefs of Dalecarlia have begun to

be formed at different times, the length of the periods of growth has varied, and the thickness and extent of the reefs have on that account varied much. In the big reef bodies, where in the limestone quarrying the surrounding stratified rocks have not yet been reached, they can sometimes be seen in the immediate neighbourhood of the reef, as a rule as nearly vertical strata. This is the case at Osmundsberg, at Boda and other places.

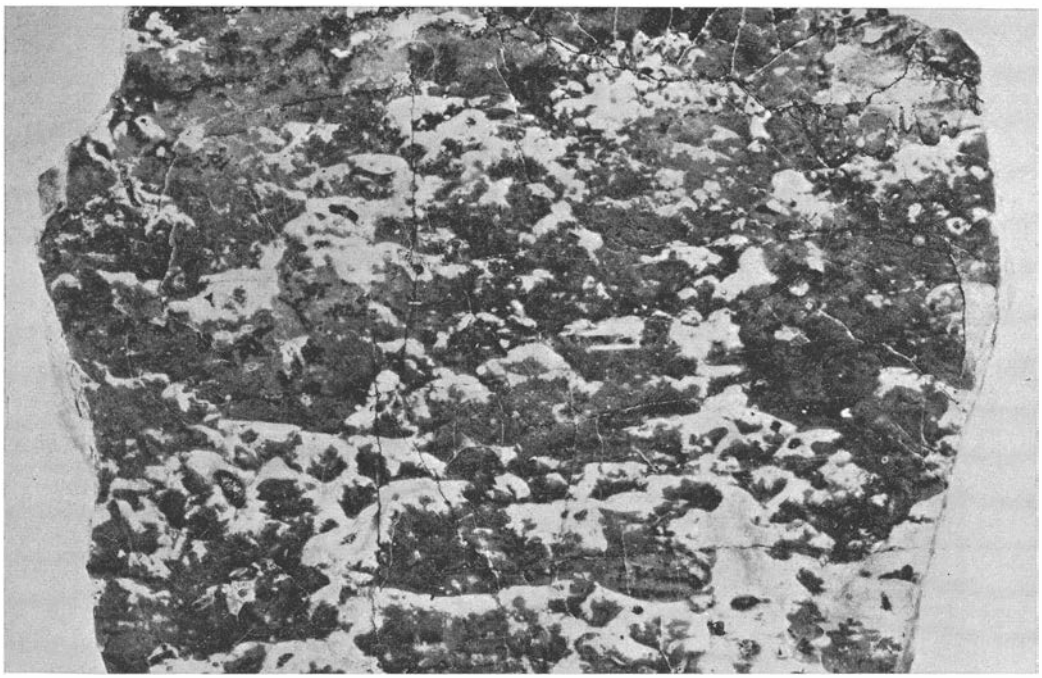

Fig. 70. Flamy reef limestone. Kallholn. (Pl. 1208.) — 1/1.

Reef-building organisms.

When one is faced with a section in the reef limestone of Dalecarlia one gets an immediate impression of the peculiar character of the rock. The structureless, unstratified mass is strongly in contrast to the surrounding stratified sediments. On a closer examination one finds in the first place that the limestone is cracked, brecciated and often traversed by large fissures, filled with argillaceous or calcareous material, quite different from the rock of the reef. Variations in colour are seen everywhere: red, green, grey, and black portions.

Fossils are here and there found so abundantly that they entirely impress the rock. Trilobites, brachiopods, or cephalopods are somewhat met with in mass-accumulations; crinoid fragments as well, the latter, however, mostly in marly fillings within the reef.

One may have studied a reef rather long and rather thoroughly before one has observed any reef-forming organisms. I myself did not notice them until I began to reflect upon the reason for the reef character of the rock. If one looks for organisms that can have formed the reefs, one will soon find that they are not lacking though not conspicuous. But they are preserved in a way that makes it difficult to identify them. During the diagenesis of the rock these fossils have

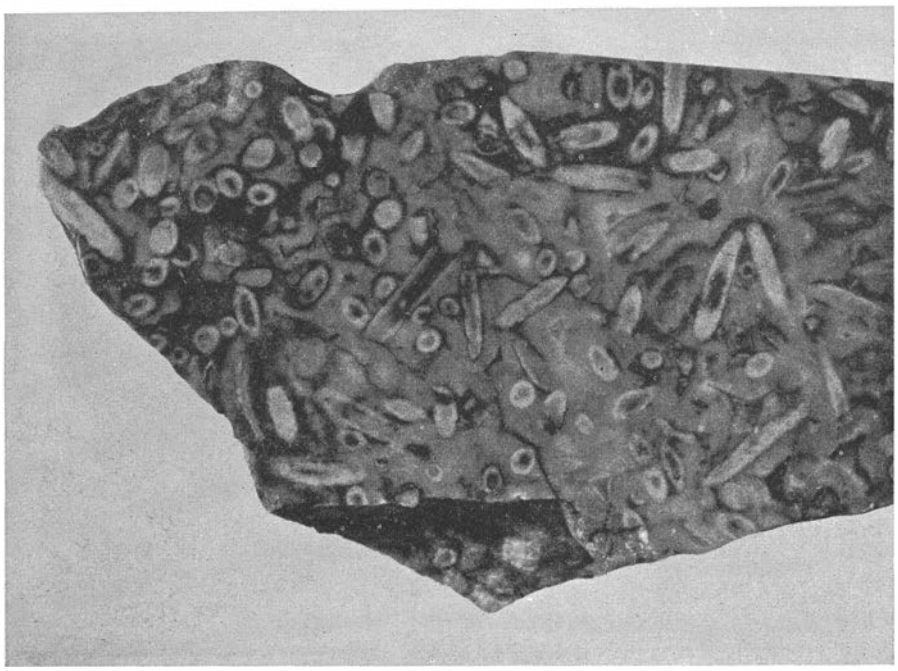

Fig. 71. Calcareous algae (*Paleoporella*). Osmundsberget. (Pl. 918.) — 1/1.

recrystallized and along with the surrounding matrix formed a compact mass. Through brecciation, infiltration of petroleum or precipitation of calcium carbonate the primary elements of the reef have become still more contourless.

It is clear that the calcareous organisms which have bound together the loose fragments of the reef and prevented the stratification must be regarded as reef-builders, even if they have not appeared as a coherent, firm frame. The reefs of Dalecarlia have not been built up in the same way as the coral reefs or the stromatoporoid reefs. Corals and stromatoporoids, hydrocorals and serpula tubes appear in reefs directly grown on each other into big, firm, irregularly branched masses, in and around which silt and fragments accumulate. Calcareous algae may appear essentially as connecting crusts. Because of their characteristic appearance and sometimes typical form and the absence of plain structure the reef-formers

appearing in the Leptaena limestone must, according to the author's opinion, be considered as calcareous algae.

The calcareous algae in the reefs of Dalecarlia have formed carpetings which may certainly have been stored on each other, but which have often been separated by silt and fragment layers. In a higher degree than other reef-builders the



Fig. 72. Reef limestone with calcareous algae. — Osmundsberget.

calcareous algae have grown on and between the loose masses, and by that their form has often become highly irregular and indistinct (fig. 70).

The calcareous algae in the Leptaena limestone are of different types. Best preserved and easiest identifiable are the little cylindrical fragments of *Paleoporella* (fig. 71). But these are of no importance as reef-formers. How many different forms there exist of the more spread algae appearing in larger masses can hardly be decided, as the organic structure has been almost entirely deleted and the external form has been more dependent on the possibilities of growth, surrounding accumulation of fragments etc., than on the character of species.

Seldom does one find freely developed algal masses, isolable from the surrounding matrix.

In the adjoining fig. 72 thin, slightly bended laminae of calcareous algae are seen. Locally such appear in great abundance in the reefs. The thickness varies from some millimetres to some centimetres. Sometimes they are quite compact, in other cases divided into laminae of growth (fig. 73 and 75).

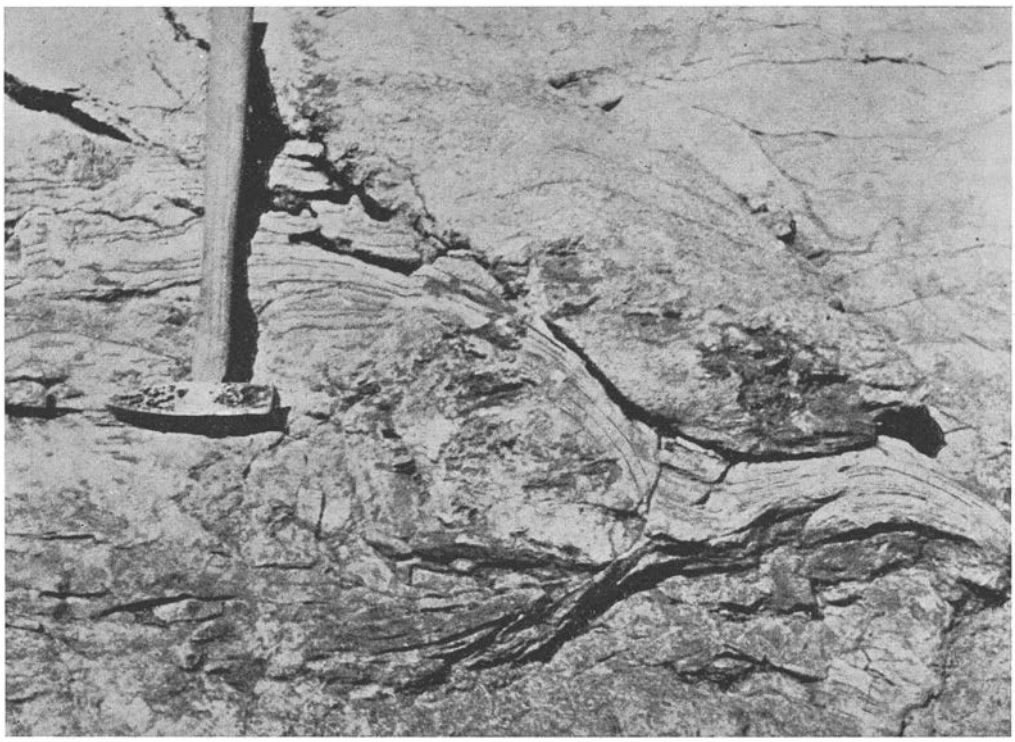

Fig. 73. Reef limestone with calcareous algae. — Osmundsberget.

Arched, calotte-like forms are found scattered in all the reefs. They have as a rule a lamellar structure which comes out in the weathering of the rock (fig. 74) or in different-coloured layers. Semi-elliptical, semi-cylindrical (fig. 76) or more irregularly arched forms show the same structure.

Under the microscope the original organic structure never appears, though the laminae of growth do. The considerable dissimilarities these show (fig. 77—80) can (to the extent they are primary) be interpreted as characteristics of different kinds or forms. The thickness of the individual algal layers is often less than 1 mm. and they are sometimes divided into laminae of growth with a thickness of about $^1/_{10}$ mm.

Though the calcareous algae of the Leptaena limestone are not so well preserved that they can satisfactorily be assigned to species or even genus they still show in form and development characteristic features, which are found again in other, previously described fossil algae. I do not hesitate to assign some of those mentioned here to the »genus» (or rather group) which goes by the name of

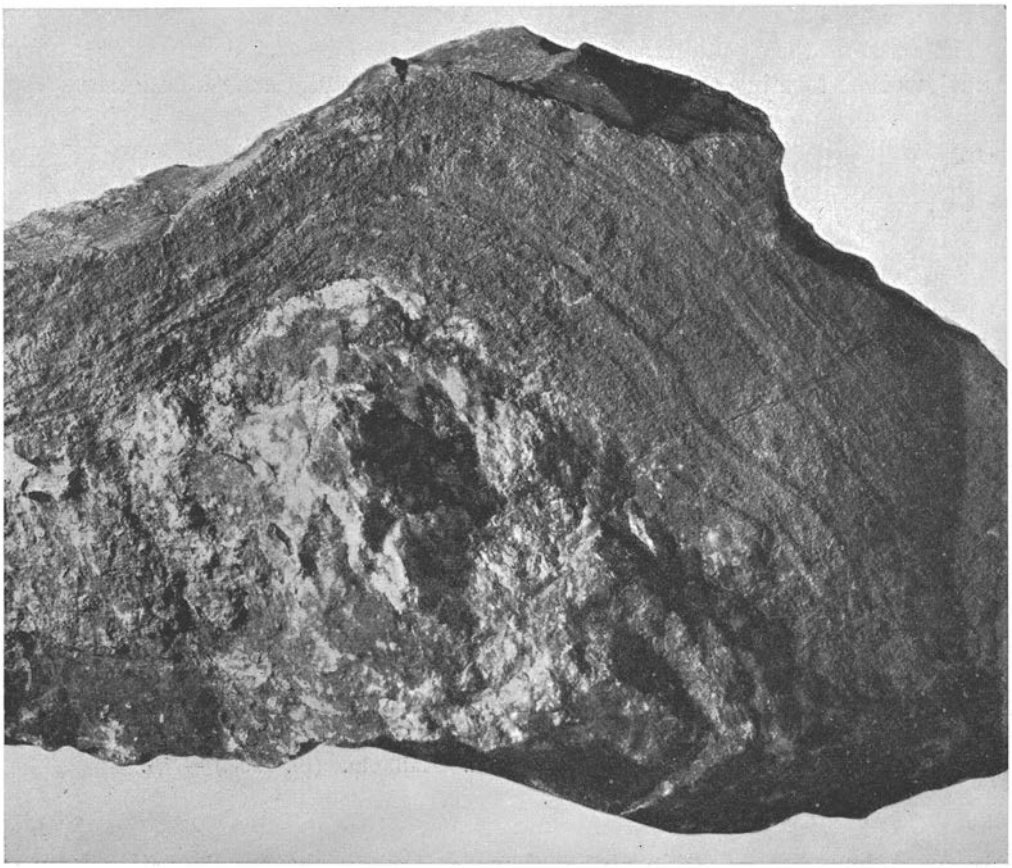

Fig. 74. Calcareous alga of *Collenia* type. Kallholn. (Pl. 1207.) — 1/1.

Collenia and which we know well through works by WALCOTT, RUEDEMANN, WIELAND, FENTON, etc. PIA thinks that these lime bodies have probably been formed by blue-green algae, and he considers it possible that several different species have built up the algal mass in common. A similar co-operation has been proved for other calcareous algae, e. g. *Sphaerocodium* (cf. HADDING 1933, p. 15).

Corals are found in several places in the reef limestones of Dalecarlia but as a rule only in scattered colonies. Here and there the limestone is nevertheless to a considerable degree built up by corals. This is the case for instance with some

portions of the upper part of the reef at Osmundsberget. Many different forms have been observed belonging to the genera *Halysites, Favosites, Heliolites, Cystiphyllum, Syringophyllum,* etc.

Remaining Calcareous Organisms in the Reefs.

The bulk of the Leptaena limestone consists of larger and smaller fragments of various lime-forming organisms and of calcareous mud. Inorganic detritus plays

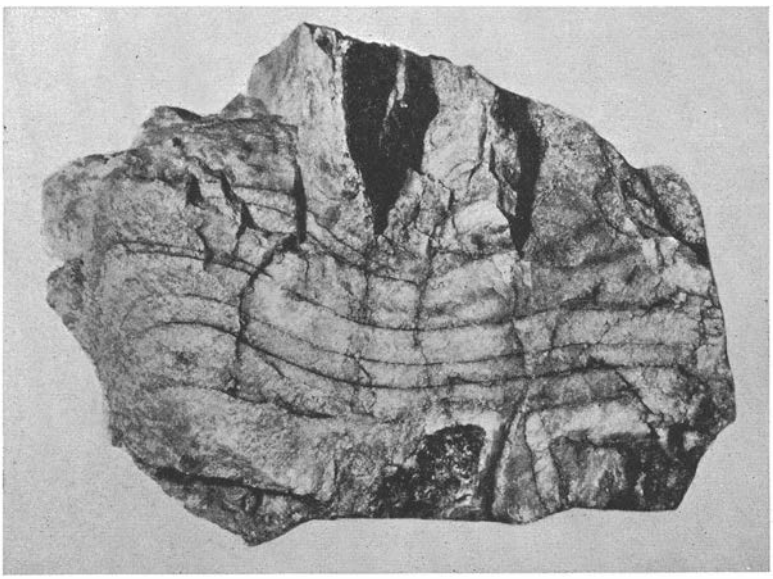

Fig. 75. Calcareous alga, laminated. Kallholn. (Pl. 1206.) — 1/1.

only an unimportant part in the reef mass. Among the fossils trilobites are found in the first place (Warburg 1925). They are met with nearly everywhere. Sometimes the pygidia are enriched so that they entirely imprint the rock. The same may be the case with cephalopods, above all the orthoceratites. The rock rich in trilobites or cephalopods changes into normally developed reef limestone without any definite limit.

Brachiopods occur scattered in the reef limestone. The shells are also found enriched in marly beds traversing the reefs. Both at Osmundsberget and at Kallholn such brachiopod horizons are to be seen.

Lamellibranchs form a characteristic element in the limestone and they have also a certain stratigraphical value (Isberg 1934).

Gastropods are found here and there, yet only sparsely.

Cystoids are represented by several species but not in abundance.

Bryozoans appear along with other fragments, but never in such quantity that they can be characterized as rock-forming.

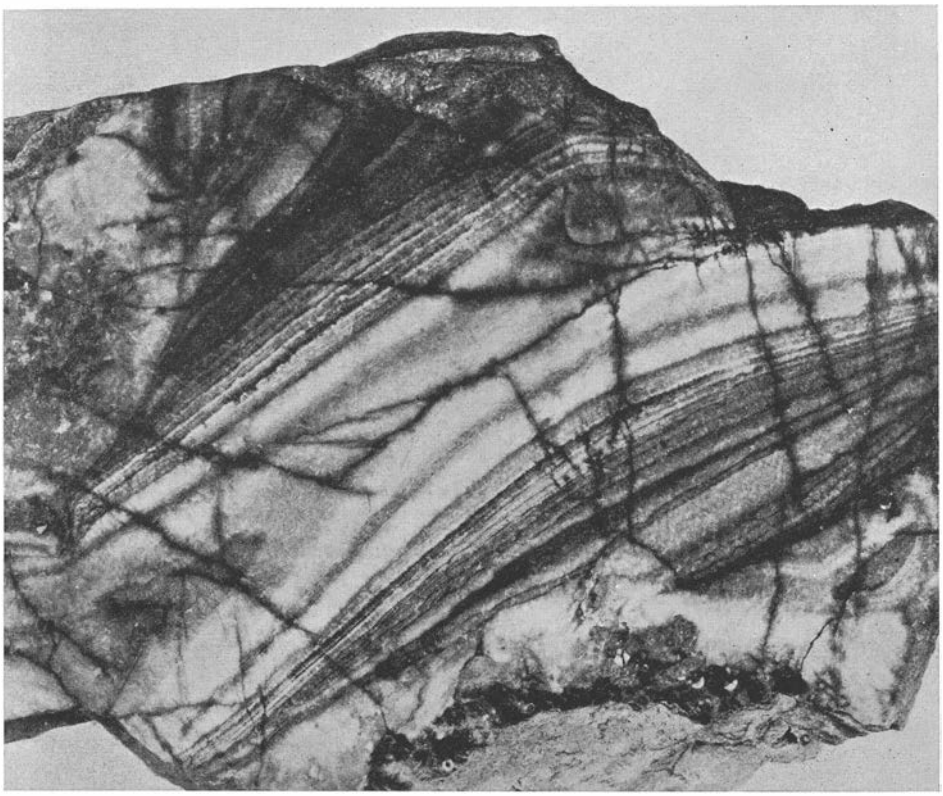

Fig. 76. Calcareous alga. Section through the base of semicylindrical lime body. Amtjärn. (Pl. 1204.) — 1/1.

The Diagenesis of the Reefs. — Fissures.

The recrystallization of the organic calcareous skeleton and the cementation of the loose masses are the most important diagenetic processes in the reefs. (Concerning these processes see also p. 112.)

In connection with the tectonic movements, the tilting of the series and the dislocation of the reef mass the limestone was brecciated. Deep fissures were formed and filled with fragments detached from the walls or with material washed down from the opening of a fissures. Some fissures contain balls of limestone (Leptaena limestone or arenaceous limestone) with plain chemical corrosion and matrix of clayey mud, other fissures are rich in pyritic marl, others contain black

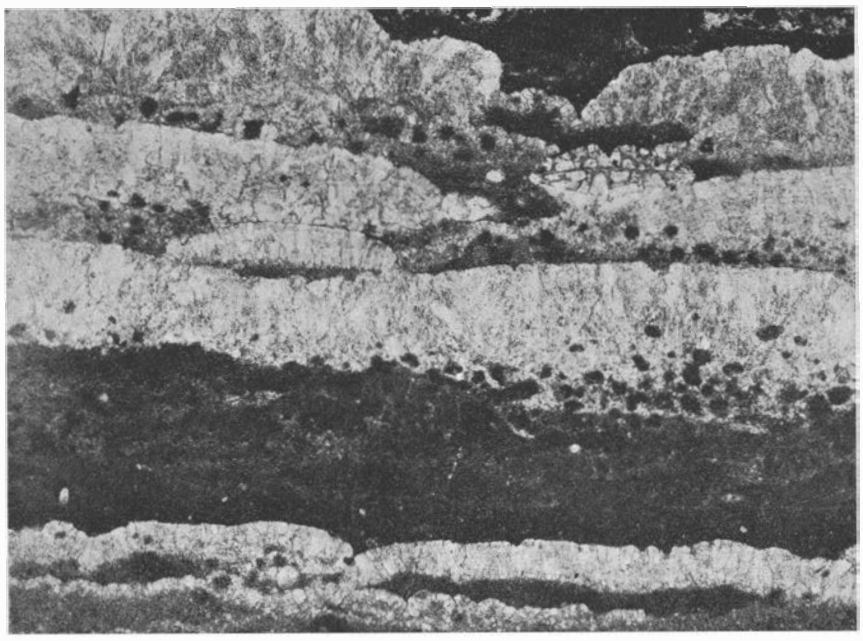

Fig. 77. Layer of calcareous algae. Kullsberg. (Pr. 6280, pl. 1202.) — 10 ×.

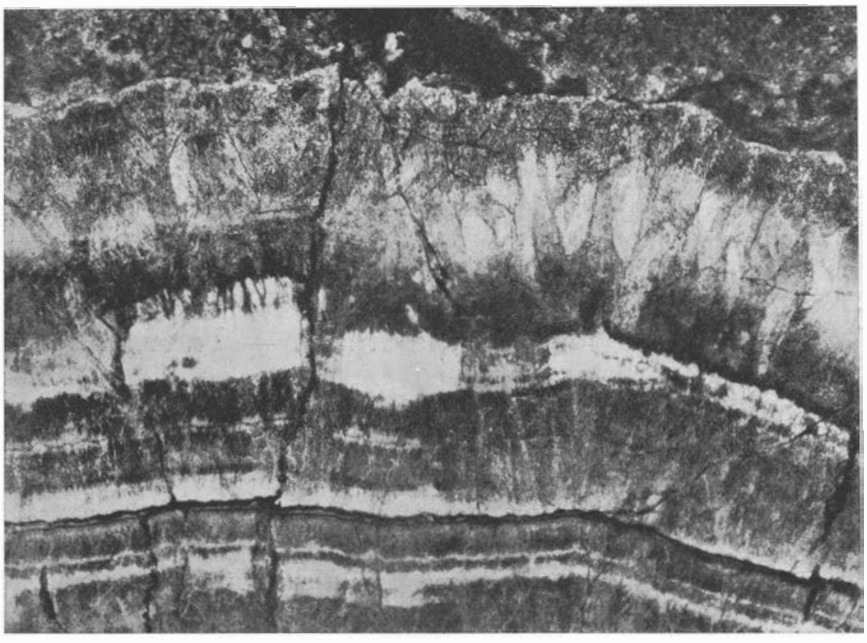

Fig. 78. Layer of calcareous algae. Kallholn. (Pr. 6282, pl. 1196.) — 10 ×.

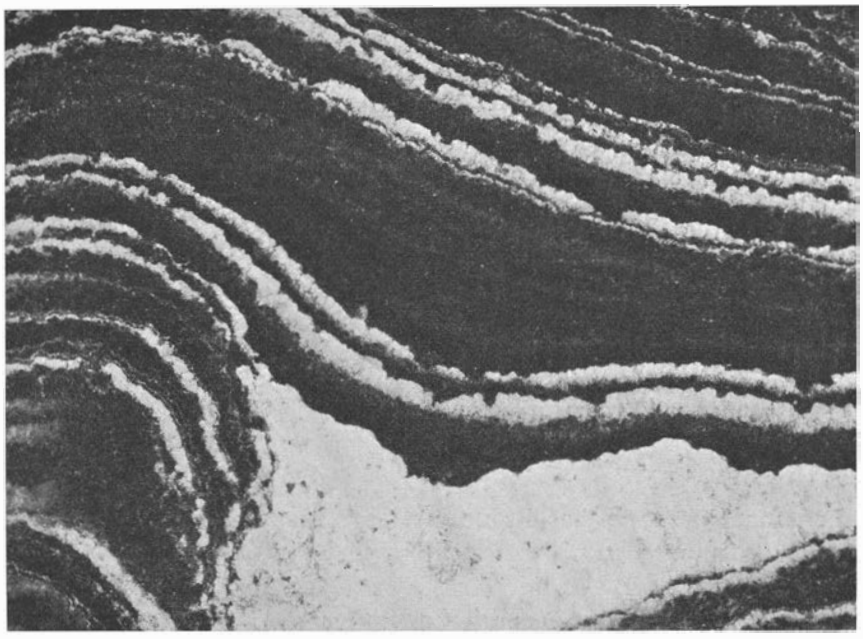

Fig. 79. Layer of calcareous algae. Osmundsberget. (Pr. 6284, pl. 1201.) — 10×.

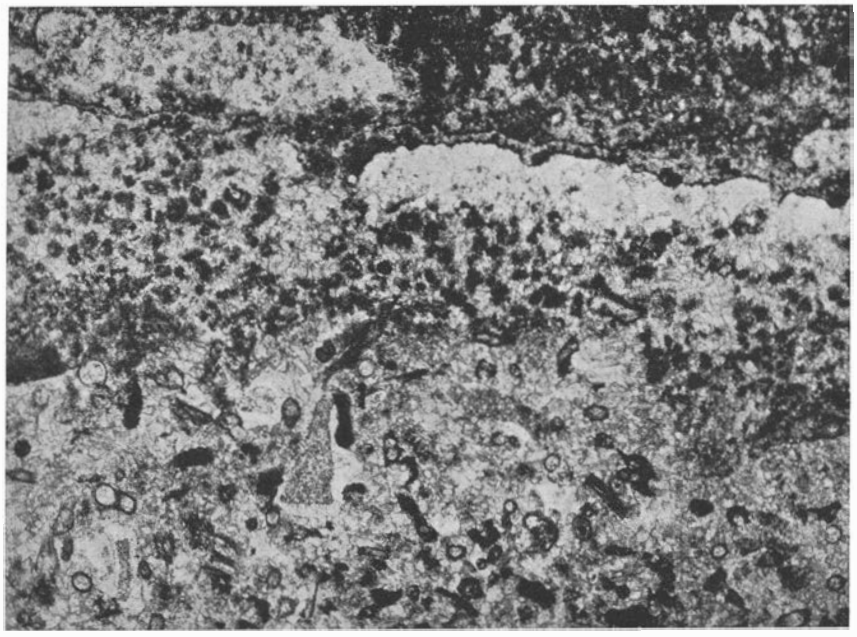

Fig. 80. Layer of calcareous algae. Osmundsberget. (Pr. 6289, pl. 1200.) — 10×.

shaly substance (Isberg 1918, Troedsson-Rosvall 1926, Thorslund 1932, Isberg 1934). The fissures are of different age, Silurian or younger. At Osmundsberget the author has observed a postglacial fault traversing the abraded and striated reef surface. The throw was about 0.5 m.

Some of the fissures in the reefs of Osmundsberget have one wall covered by an algal limestone of a peculiar kind, formed as a covering on the almost vertical wall. It reminds one of dripstone formation and has earlier been described by the author under the name of *Teicholite* (fig. 81). This formation too is likely to be of Silurian age (Hadding 1939).

The Leptaena Limestone compared with some other Limestones.

The Leptaena limestone has its nearest correspondence in the reef limestones which appear in upper Ordovician at Mjösa in Norway (Holtedahl 1909, p. 58). According to Kiaer (1921, p. 501) the Mjösa limestone ought to be considered as a calcareous deposition and coral reef formed at the end of the time of the Chasmops group. We have no close description of the limestone but Holtedahl (1909, p. 58) states, that it has been formed through »enormous masses of corals, monticuliporids, echinoderms etc., the structure of which has been destroyed». It is to be noticed that also the stratified rocks in the same series are rich in calcareous algae (cf. the indications Rhabdoporella limestone, Coelosphaeridium shale, Cyclocrinus limestone, etc.).

In his comprehensive investigation of the Hovin group in the Trondheim area Kiaer (1932, a) gives a close analysis of the Kalstad limestone, which he describes as a light reefy limestone (p. 22) built up of calcareous algae and corals. The algae are described by Hoeg (1932, p. 63), the corals by Kiaer (1932, a, p. 103). Concerning the age of the Kalstad limestone Kiaer writes (1932, a, p. 34): »I do not believe that the fauna of the Kalstad limestone is against a parallelizing with the Stinchar limestone of Scotland» (at Craighead) and »There also might be a possibility of the Kalstad limestone being parallelized with the Mjös limestone, which according to my latest investigations must be taken to the uppermost portion of the Middle Ordovician.» The limestone at Craighead do not however, as Kiaer supposed, belong to the Middle Ordovician but to the Upper Ordovician (cf. Ulrich 1930, p. 84) and like the Mjösa limestone it may be equivalent to the Leptaena limestone. The Craighead limestone is partly developed as reef and then essentially constructed of calcareous algae and corals.

Within the Balticum too correspondances to the Leptaena limestone are found. As erratic blocks a dense, hard limestone, so-called Baltic limestone (Östersjökalk), is found from Åland to North Germany, which according to Wiman (1893, p. 10) is equivalent to the lower part of the Leptaena limestone and the Wesen-

berger and Lyckholmer strata in Esthonia. Whether this limestone appears as reef is not known, nor if it contains calcareous algae in great numbers.

In Gotland erratic blocks of a grey, crystalline rock have been collected, which WIMAN has described as identical with a limestone in the Borckholmer strata of Esthonia. Thus it corresponds to the upper part of the Leptaena limestone and has great faunistic affinity to this. About the rock WIMAN writes (1901, p. 152): »Es lässt sich zwar recht gut denken, dass Kalkalgenfragmente einen integrieren-



Fig. 81. Younger calcareous algae (*Teicholite*), crust on a fissure wall in the reef. — Osmundsberget.

den Teil desselben ausmachen, aber das Aussehen dieses Kalksteins erinnert nicht im entfernsten an die dem lithographischen Stein ähnelnden, aus *Paleoporella* und *Vermiporella* gebildeten Kalkvarietäten, welche sonst im jüngeren Untersilur des baltischen Gebiet so häufig vorkommen.» It is not known if this limestone appears as reef. Its correspondence in Esthonia is bedded. About this SCHMIDT writes (1881, p. 40): »Dem Gestein und den Petrefakten nach stimmt — — — der Leptaenakalk von Dalarna so vollständig mit unserm Borckholmer Kalk überein, dass ich ihn als direkte Fortsetzung betrachten möchte.»

Petrographically the Leptaena limestone seems to have its most obvious equivalence in the Kildare limestone in Ireland and the Keisley limestone in the

Lake-district in North England. MARR (1892, p. 101) pointed out this, yet without wishing to speak of the character of these limestones. He says about the limestone at Keisley: »It is not needful to discuss the origin of the nodular masses of crystalline limestone in this place». — In connection with an investigation of the fauna in the Keisley limestone COWPER REED has further laid stress upon the great correspondence between this limestone and the Leptaena limestone. He also stresses (1897, p. 104) »its reef-like nature and mode of occurrence, as a local thickening of an elsewhere thin band of rock». He gives no explanation of their origin. — A comprehensive survey of the paleontological resemblances between the Leptaena limestone and other corresponding rocks mentioned here was made by TÖRNQUIST in 1919. Nor in this work are there any attempts to explain the origin of the limestone. Nowhere has one observed reef-building organisms, and the reef-like appearance has therefore been left unexplained.

As the author has already pointed out the reason why the reef builders have not been observed lies partly in the fact that they do not appear as coherent stocks but only as connecting masses most often of an irregular form, partly in the fact that their organic structure has been almost completely deleted. The reason for this latter case lies possibly in the disposition for recrystallization that calcareous algae have. In his interesting and constantly topical observation of the rock-forming calcareous algae in the bay of Naples JOHANNES WALTHER has illustrated the change of the calcareous algae into a structureless, dense limestone. WALTHER writes (1885, p. 343): »Das in Kalkgesteine eindringende Wasser bringt nicht immer die zu einer Metamorphose nöthige Kohlensäure mit, sondern findet dieselbe im Gestein vor; und diejenigen Kalkablagerungen, welche phytogen sind, werden nothwendigerweise umkrystallisirt, während nichtphytogene Kalke meist verkittet und verfestigt, aber nicht structurlos werden.»

Calcareous algae have to a great extent built up limestones within different formations. WALTHER (1885, p. 347 ff.) mentions as an example the upper Triassic Dachstein limestone at Dachstein and Totes Gebirge, and he proves that this rock already in Lias must have been recrystallized and firmly cemented.

The origin of the big reefs in the Middle Trias of the Alps has been a riddle which many scientists have tried to solve. The Dolomites have fascinated and tempted not only through their gigantic forms but also through the secret of their origin. The reefs of Schlern dolomite reach a thickness of several hundred metres but they do not show any plain reef-building organisms. One has sometimes expressed a supposition that this rock has been formed by calcareous algae. One of the best experts of rock-forming algae and at the same time of the Dolomites, JULIUS PIA, speaks, however, as late as 1940, very carefully on this question. He writes (OGILVIE GORDON and PIA 1940, p. 95). »Es bezweifelt heute wohl niemand dass der Schlerndolomit ein organisches Gestein ist. Die Reste der ihn aufbauenden Organismen sind aber zum sehr grossen Teil unkenntlich oder doch unbestimmbar geworden — — —. Crinoiden, Gastropoden usw. sind gelegentlich zu finden, werden aber bei der Entstehung kaum eine massgebende Rolle

gespielt haben. Verhältnismässig am reichlichsten trifft man Korallen und Kalkschwämme.» *Diplopora* occurs locally in abundance, and as »Blaualgen-Knollen» some formations can possibly be interpreted. —- »Im ganzen wird man wohl vermuten dürfen, dass die Organismen im Schlerndolomit ähnlich vergesellschaftet waren, wie in einem rezenten Korallenkalk, in dem ja auch oft die Korallen an Masse nicht die erste Rolle spielen. Algen traten vielleicht etwas mehr zurück, Kalkschwämme mehr hervor, als in den jüngeren Absätzen gleicher Facies.»[1]

The author visited the Dolomites in the summer of 1938 and devoted some days to the study of the dolomite in the Schlern massif (Sciliar). He could only state the same as other scientists had done, that the reef builders proper could not be observed in the field. Nor has a careful study of the material brought home made a certain conclusion possible. Traces of algal structure, rather like that of *Lithothamnium,* have yet been observed in thin sections. With regard to that and still more on account of the petrographical correspondences that are found between the algal reef limestone in Dalecarlia and the Schlern dolomite, he considers it likely that the latter too is for the most part built up of calcareous algae. WALTHER's above quoted observations concerning the tendency of the calcareous algae to recrystallize seem to him to give a natural explanation also of the fact that we have not found nor can expect to find the reef-building organisms in the Schlern dolomite.[2] This rock is also exceptionally poor in argillaceous detritus, which can protect isolated parts of the rock against circulating water and in this way prevent or counteract their recrystallization. One finds as a rule the structurally best preserved fossils in the most clayey or marly parts of the reefs, and the recrystallization is most thorough in the rocks or parts of rocks which like the Schlern dolomite are relatively free from clay.

Also in Russia (USSR) the author has had occasion to see some reefs, which according to his opinion are mainly built up of calcareous algae. In the Bashkirian ASSR, E of the city Sterlitamak (about 53° 30′ N, 56° 0′ E) some isolated, conic mountains (»shikhans») lie, with a core of reef limestone of Permian age (Artinskian). The rock is locally rich in fossils, especially brachiopods, bryozoans, crinoids, lamellibranchs, and gastropods. Simple corals and calcareous algae have been observed. But one cannot get any comprehension of the reef-building organisms by a narrow examination of the rock in the field. It appears as an unstratified, dense, splintery, faintly yellow limestone (fig. 82). Under the microscope a lot of little fragments of bryozoans and other fossils appear and in some sections fine calcareous needles or fibres. It is hardly likely that these originate from calcareous sponges, as the more compact and enduring parts of these

[1] Also in another place (1937, p. 60) PIA points out the importance of the calcareous sponges as rock formers. He writes: »Unterschätzt wird meiner Meinung nach im allgemeinen die Bedeutung der Spongien als Gesteinsbilder. — Für den Schlerndolomit scheinen in erster Linie die Synconen wichtig zu sein.»

[2] Generally the *Calcispongiae* are, like corals, well preserved though their microstructure may be quite deleted.

organisms have not been found. It seems to the author as if one had reason to count on calcareous algae as connecting organisms in this rock to an essential part built up of fragments.

The oil-bearing limestones of the Ishimbaevo oil field are stratigraphically

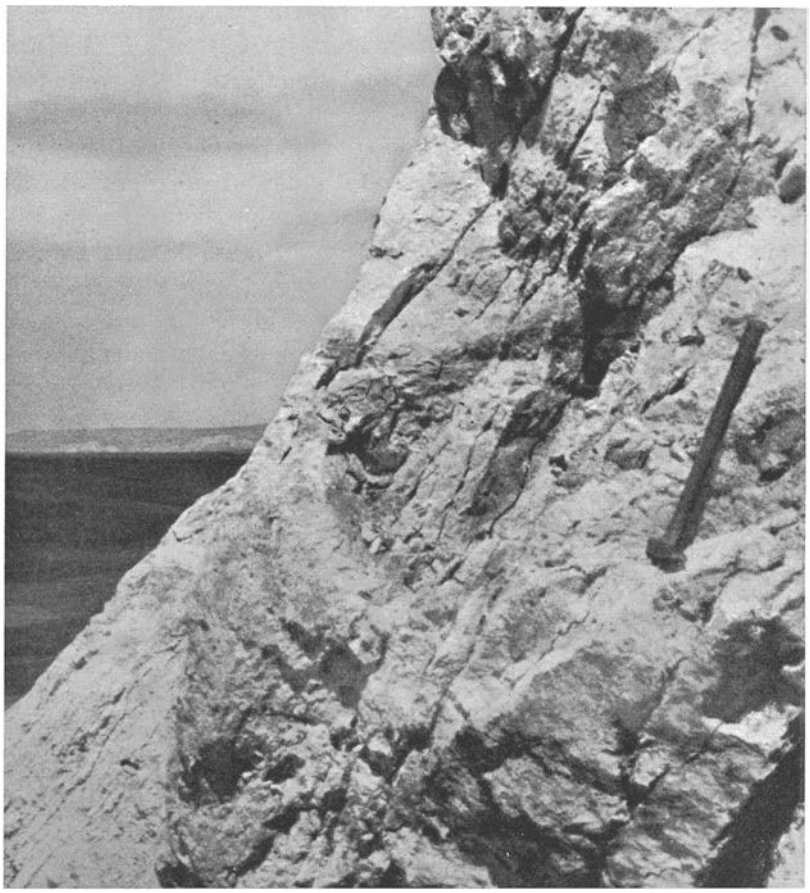

Fig. 82. Artinskian (Permian) reef. — Tra-Tau shikhan. Bashkirian ASSR.

and petrographically identical with the reefs of the shikhans.[1] The reef character of the limestones has, according to A. Blokhin (1937, p. 24), first been pointed out by D. V. Nalivkin, and in the reefs and the surrounding limestones the oil geologists have distinguished »five chief, most widely spread facies: the bryozoan, crinoidal, hydroid, fusulinoid and algal facies». Coral limestones are also mentioned. The author has examined samples of them all and ascertained that the Russian geolo-

[1] The reefs of the Sarga horizon by Sylva River, SE of Perm, are of the same type and on the whole of the same age.

gists (i. a. A. Trochimik) have rightly interpreted the rocks. Pure reefs of corals or hydrozoans have not been shown, no more than of sponges or algae. The reef lumps are surrounded by crinoid limestone, in its turn enclosed in foraminiferal limestone. The reefs occur as barrier reefs on Devonian layers, folded along the longitudinal direction of the Urals.

The high cliff Besh Barmak in the Siazan oil field of Azerbaijan reminds one in a high degree of the peaks of the Dolomites. It is also built up of almost the same rock as these, viz. by an Upper Jurassic reef limestone, partly dolomitized. In the samples of the reef which the author has collected, no corals, hydrocorals or other such reef-building organisms are seen, but the rock is rich in calcareous algae of different kinds.

The calcareous algae appear, it is true, to a large extent as rock builders in the European series of strata, not least in Gotland, but for the above-mentioned reasons they have easily been overlooked in the reefs. They are more prominent in American reef limestones, and we have the best descriptions of these organisms as reef builders from U. S. A. This is not the place to give a review of these works, and the author can only refer to the references and the names Walcott, Fenton, Bradley, Ruedemann, Ulrich, Twenhofel, Black, Cumings. The author intends to take up the question of the structure and various form of the rock-forming algae in another place and he will then get an opportunity of returning to the works quoted and others.

THE DANIAN REEFS.

The marine limestones which form the upper part of the Cretaceous series in Central and Western Europe are found also in southernmost Scandinavia. There they pass into pure littoral sediments, such as fragment limestones, sandstones or conglomerates. In the youngest part of this series, the Danian limestone, larger or smaller reefs are also found. This formation is best developed, best exposed and best known in Denmark, at Faxe in Sjælland, and we can look forward to a comprehensive paleontological and petrographical account of this deposit by the Danish geologists. The reef limestone at Faxe has for several decenniums been the object of intense quarrying and the geologists have for a long time devoted interest and study to it. Several works on this formation have already been published, i. a. by JOHNSTRUP, FISCHER-BENZON, RAVN, BRÜNNICH NIELSEN etc.

In Sweden there are Danian sedimentary rocks only in south-western Scania, and there as a direct continuation of the corresponding layers in Denmark. The Danian reef limestones in Scania were observed and described among others by JOHNSTRUP, LUNDGREN, and HENNIG. The reefs have been best exposed in the large quarry at Limhamn (Annetorp) just south of Malmö. At present (1940), however, no reef bodies are visible in the walls of the quarry. Thus there is now no opportunity for field studies of the reefs and I have therefore to be content with referring to the results of older investigations.

The Stratigraphical Appearance of the Danian Reefs.

The Danian series rests on Senonian chalk. The boundary layers are not exposed in Sweden but very accessible in Denmark, where the following sediments have been distinguished.

Paleocene	Glauconitic limestone
Upper Danian	Fragment limestone Calcareous sand and conglomerate
Middle Danian	Bryozoan limestone Coccolite » Coral »
Lower Danian	Cerithium limestone Clay
Upper Senonian	Chalk

The Danian series consists in its lower part entirely of stratified rocks. The reefs are found only in the middle part of the series, but this too is essentially built up of stratified limestones.

The Size, Form, and Appearance of the Danian Reefs.

The Danian reefs have in Sweden been observed only where the limestone has been quarried after the Pleistocene glacial sediments have been removed. As a matter of fact reefs have been found only in one place, viz. in the large limestone quarry of the cement factory at Limhamn. Of course one cannot form an opinion of the extent of the reefs within the Swedish-Danian area merely from this locality. Consequently we do not know if the reefs have been arranged as garlands along the coast or if they have formed more irregular groups. The large reef at Faxe in Sjælland, 60 km SW of Limhamn, lies, as far as we know, isolated from the Scanian reefs.

The Danian reefs of Scania have an irregular and varying form. They often appear as extended lenses or nodular lumps (fig. 83—84). Some of the small reefs at Limhamn had in the beginning of their growth the form of an obtuse cone set on its apex, but their upper part was more extended. Most of the reefs and above all the larger ones have a decided horizontal extension.

The size and form vary. At Limhamn Hennig measured in 1897 a reef 150 m long, 30 m wide and 4 m in thickness and another with a diameter of 120 m and a thickness of 11 m (Hennig 1899, p. 74). Most of the reefs exposed at Limhamn have had a diameter of only 20—50 m. The reef of Faxe is about 1000 m long, 500 m wide and about 40 m in thickness.

The Danian reefs lie enclosed in stratified limestones. These are petrographically and paleontologically of two different types: partly dense, built up of microorganisms (coccolites, foraminifers, etc.), partly granular or porus, essentially consisting of bryozoan fragments. Both types are remarkably pure with a varying but always small percentage of inorganic detritus. Thin clayey layers are found here and there between the banks. Flint balls or coherent flint layers are common at some levels, especially in the dense limestone beds. Those interbeddings emphasize the parallel structure and, being absent in the reefs, they sharpen the contrast between the reefs and the stratified rocks.

The Constituents of the Reefs.

The reefs consist of reef-building organisms, of other lime-depositing organisms, of calcareous fragments and mud, of authigenic, inorganic calcium carbonate, and of inorganic, usually argillaceous detritus.

The primary firm frame of the reef is rich in reef-forming organisms; the other

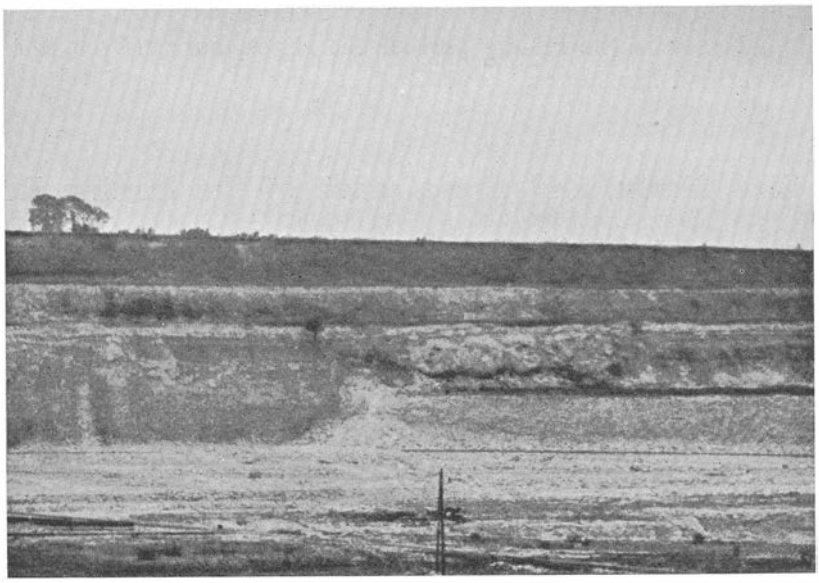

Fig. 83. Coral reef in stratified limestone. Danian. — Limhamn, Scania.

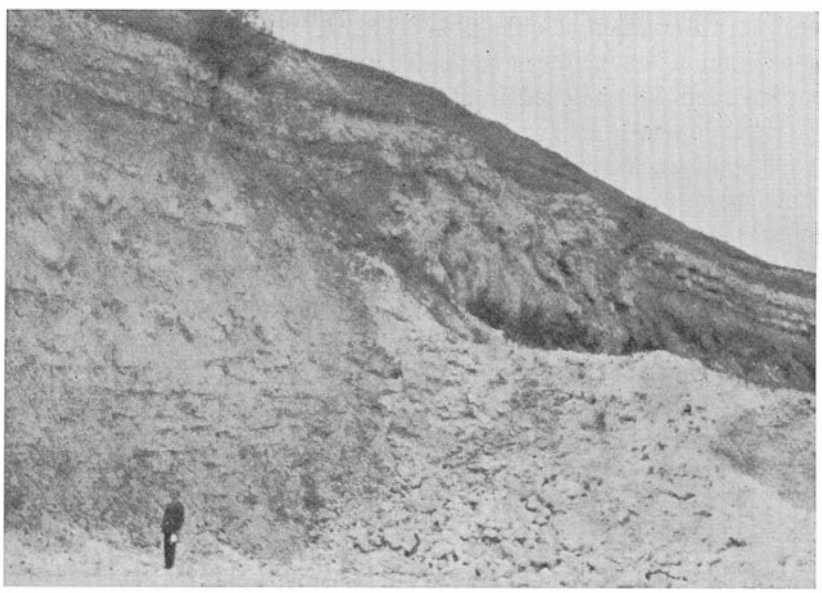

Fig. 84. Coral reef (same as in fig. 83).

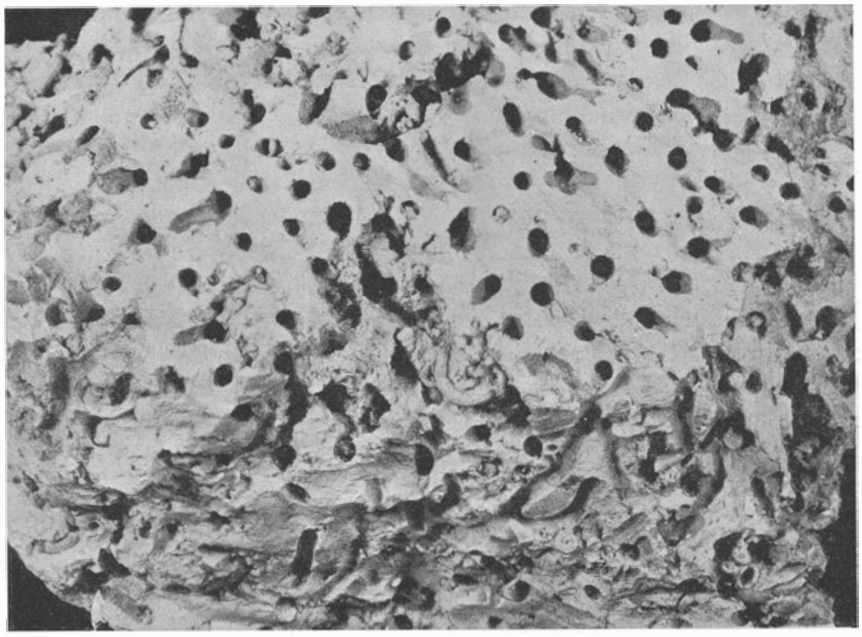

Fig. 85. Reef limestone with moulds of branched corals. Danian. Faxe. — 1/1.



Fig. 86. Coral reef limestone. A portion without matrix. Danian. Faxe. — 1/1.

constituents form a matrix which during diagenesis can assume a very considerable solidity.

The skeleton of the Danian reefs is built up of corals and hydrocorals and to a less extent of serpula tubes and bryozoans.

The corals are as a rule so commonly and so well represented in the Danian reefs that the rock is with every reason called coral limestone.[1]

JOHNSTRUP (1864, p. 22 a. f.) has described in detail the different states of preservation of the corals and the varying character they give the rock. The coral stock primarily formed by the animals is seldoms preserved, and if so it is as a rule recrystallized. The coral stock has during the reef formation been embedded in calcareous mud and often one finds moulds of the wholly or partly dissolved coral stock (fig. 85). If the rock is dense it does not mean that the original or recrystallized coral stock is left; it is as often or oftener so that the cavity formed at the dissolution of the coral stock has later on been filled with secondarily crystallized calcite.

Among the corals the branched *Hexacoralla* have the greatest importance as reef builders and especially two forms ought to be mentioned: *Dendrophyllia candelabrum* HNG and *Calamophyllia faxensis* BECK (cf. HADDING 1933, p. 38). Here and there in the reefs the cylindrical branches of these corals are found in situ without matrix (fig. 86). The construction of the reef stock is in such places conspicuous.

Cup corals, for instance *Parasmilia*, are commonly found to have grown on the reef stock. They are scarcely to be considered as reef formers proper, even if they contribute to form the rock. Along with these corals an abundance of fixed crinoids are found, especially *Cyathidium*.[2]

Alcyonaria and hydrocorals occur in the Danian reefs as in recent reefs along with the corals. Locally they are represented by decidedly rock-forming species, as for instance the genera *Moltkia* (fig. 87) and *Gorgonella*. By their widely extended basal parts and often very strong branches they have effectively contributed to building up the reef and holding its loose portions together. They are often covered by bryozoans, serpula tubes, and dense calcareous crusts, possibly formed by calcareous algae (cf. HADDING 1933, p. 42).

Contrary to the corals and hydrocorals the bryozoans are found only in fine-branched and easily crumbled forms or as thin coverings on other calcareous organisms insignificant for the rock formation. In the matrix the bryozoans play an important part, but not in the reef stock.

Serpula tubes are found rather commonly but they are not rock-forming in the Danian reefs.

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[1] After the largest and best known occurrence of Danian reefs at Faxe the coral limestone is in literature often called *Faxe limestone*.

[2] BRÜNNICH NIELSEN has devoted a close study to those and several other fossils occurring in the reef (see the references).

The crinoids too are rather common, attached as well as disrupted and crumbled. The latter sometimes form an essential part of the matrix.

The Danian reefs have, like the recent coral reefs, been a resort for numerous forms of animals, and many of these have contributed to the formation of the reef limestone. We find fossil remains of them in the matrix of the reefs. Besides

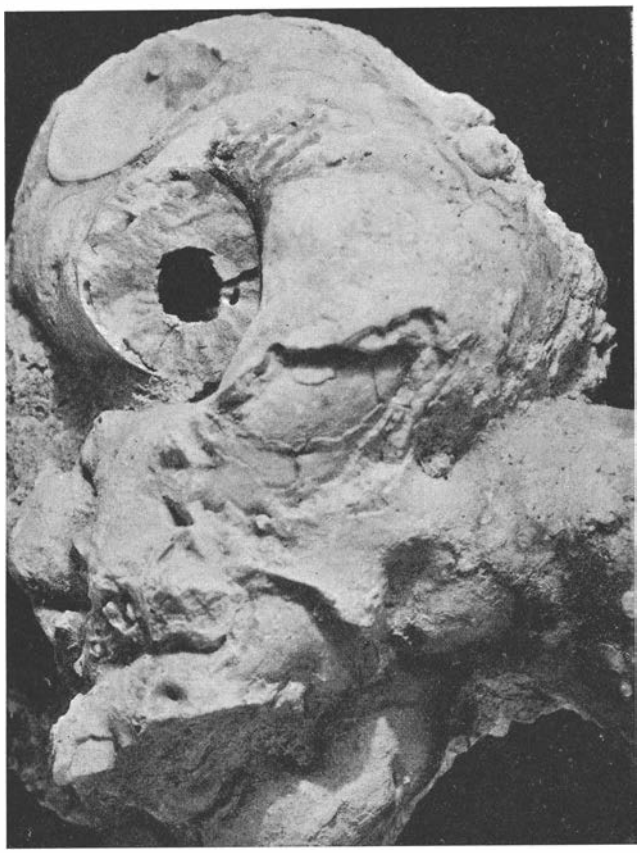

Fig. 87. Alcyonaria (*Moltkia*) of Danian reef limestone. Limhamn. — 1/1.

fragments of corals and hydrocorals I have already mentioned bryozoans, crinoids, and serpulae. Brachiopods are found in varying numbers, besides lamellibranchs, gastropods, cephalopods, crustaceans, and fishes. Also echinoids are found, though less numerously than in the surrounding stratified rocks, in which they can locally be accumulated into conglomeratic banks.

Planktonic elements, for instance coccolites and foraminifers, are not absent either, even if they are but little prominent.

Calcareous mud has been accumulated in all the cavities and clefts of the reef and it takes up, including the fossil fragments embedded, about half the reef

mass. The bulk of this fine-grained material has been produced by the crush of the fragments of corals and other calcareous organisms, detached by the breakers and rolled by waves and tide-water.

In the calcareous mud and around the coarser fragments calcium carbonate precipitated and cemented the loose particles to a more or less firm mass. How much of the cement that has been formed in direct connection with the deposition of the mud cannot be decided. The state of preservation of the rock often presumes a complicated diagenetic deformation which makes it impossible or difficult to investigate the importance of the primarily deposited cement.

The Danian reefs have a remarkably low percentage of argillaceous substance and other inorganic detritus. Also the pockets and clefts in the reef suitable to catch and hold all the fine material silted up in the water contain only an inconsiderable quantity of inorganic mud.

The Diagenesis of the Danian Reefs.

The diagenetic processes in the reefs are a direct continuation of the primary formation. The precipitation of calcite and the recrystallization of the matrix began already when the mud was deposited and were continued in the completed sediments covered by new strata.

The change of organically formed aragonite into calcite has taken place in an early stage of the diagenesis and to a certain extent it has been connected with a transposition of the calcium carbonate. The cavities after corals are the result of dissolution, the first part of this transposition (HADDING 1933, p. 40).

In the preceding (p. 120) it has been mentioned that different stages of precipitation and dissolution of the calcium carbonate can be proved in the coral limestone, and they have been described in detail by JOHNSTRUP (1864) and HENNIG (1899). The final result was that almost all traces of the finer organic structure were removed. But on the other hand the diagenetic processes have involved a great firmness of the rock. The fossils have to a large extent been preserved against being crumbled and crushed after the deposition, and when they can now be isolated they are often quite undamaged. Smaller parts inside the reef, which have avoided the strong diagenesis may form an uncemented matrix. They are real treasuries for the paleontologists.[1]

Among the diagenetic processes we also ought to count the silicification of the limestone.[2]

The silicification in the Danian reefs is less strong than in surrounding stratified limestones. Deposits of flint are abundant in the latter but never appear in

[1] We may specially mention »Ravns nose» in the coral limestone of Faxe, a portion of loose limestone out of which the fossils can be washed.

[2] Dolomitization is not proved in the Danian reefs though very well in the surrounding bryozoan limestone (NÖRREGAARD 1904).

the reefs, and neither do siliceous sponges belong to the normal reef fossils. The silica in the coral limestone has been conveyed to the rock secondarily. It occurs partly as quartz crystals on shells, partly as impregnation, in both cases in small quantities.

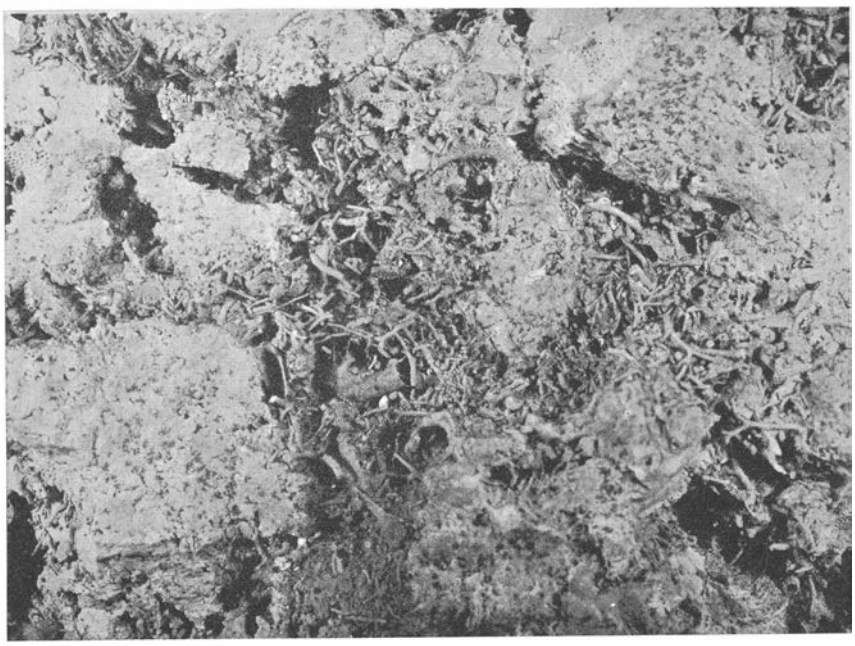

Fig. 88. Bryozoan limestone. Danian. Faxe. — 1/1.

Stratified Rocks around the Danian Reefs.

The Danian reefs are surrounded by stratified limestones. They are, as already mentioned, of two different kinds: partly compact, fine-grained limestone, coccolite limestone, partly porous fragment limestone, bryozoan limestone.

The coccolite limestone consists partly of coccolites, foraminifers, and microscopical fragments of other calcareous organisms, partly and mainly of small calcite grains of uncertain origin. The latter are of the same kind as the calcite grains in the Senonian chalk, and according to the author's opinion they have primarily been formed with the cooperation of lime-depositing bacteria (Hadding 1933, p. 11).

Among larger fossils the coccolite limestone contains cystideans, brachiopods, lamellibranchs, cephalopods, decapods, and fishes. The fossils occur as a rule only sparsely spread in the limestone, but they are well preserved, unaffected by wave action and other violent movements in the water.

The coccolite limestone contains flint balls in abundance and also continuous flint beds. The origin of the silica can be derived from siliceous sponges.

The bedding is always plain but the bedding surfaces are uneven and little marked. The stratification appears best when flint or marly layers alternate with the pure limestone beds.

The bryozoan limestone is essentially built up of fossil fragments, in the first place branches of bryozoans, coarser as well as finer, often less than 1 mm in diameter. Here and there, especially in the vicinity of the coral reefs, the bryozoans have been mixed with a lot of fragments of other organisms, such as corals, hydrocorals, echinoids, brachiopods, lamellibranchs, and gastropods (HADDING 1933, p. 77, fig. 53). The dense forms of the bryozoan limestone contain in the matrix coccolites and foraminifers.

The bryozoan limestone is often porous and slightly cemented. It may however also be dense, sometimes with a recrystallized hard matrix. There are found porous as well as dense portions, loose as well as firmly cemented within the same bed (fig. 88).

The bryozoan limestone is plainly bedded and the beds are often separated by thin marly or argillaceous layers. Flint occurs in nodules and beds.

The Formation of the Danian Reefs and Surrounding Limestones.

The Danian reefs rest on stratified coccolite limestone or bryozoan limestone. Both these rocks are marine and have been deposited in open but tranquil water and consequently not too shallow. The shells and the fragile branches of the bryozoans have not been subjected to any perceptible wave action, and therefore they must have been deposited under the limit of the normal effects of the wave-motion. The absence of calcareous algae, apart from the sedimented planktonic forms, the coccolites, is to be sure no proof of the limestones being deposited under the limit of assimilation but certainly an indication of the fact that the deposition has not taken place in the light, vegetation-rich shallow water.

The beds below the Danian reefs have thus been deposited outside the shallow water zone at a depth of more than 50 m and probably more than 100 m. The hanging wall and the lateral rocks of the reef have the same character as the foot wall, and they must have been formed under the same conditions on the whole. The stratified rocks equivalent to the reefs show that *the Danian reefs do not indicate any change in level. The reefs like the surroundings rocks are formed in relatively deep water.*[1]

[1] JOHNSTRUP (1864, p. 22) and FORCHHAMMER consider the Danian reef of Faxe to be part of a barrier reef which has gradually approached the surface of the water without reaching it. HENNIG (1899, p. 27) thought that the Danian reefs had been formed at a depth of about 150 fathoms (= 270 m).

If the origin of the reefs cannot be connected with a change in depth the reason for their formation must be sought for in other circumstances. A change of temperature, salinity, and mud content of the water may have been of importance for the origin of the reefs, and an increase of the nourishment content of the water must have favoured the development of a coralline or otherwise sessile fauna. The occurrence of corals and other reef builders demands absolutely a considerably higher nourishment content of the bottom layers of the water than that required for the deposition of coccolite limestone. The supplies of water rich in nourishment presuppose on the other hand convenient movements, currents, in the water, and the appearance of these can thus make the reef-formation possible. It is, however, to be noticed that also some of the stratified limestones, viz. the bryozoan limestones, have demanded similar conditions for their formation. Neither the rocks nor the fossils give any certain holds for the investigation of the real reasons of the reef-formation.[1]

If we examine the stratified series equivalent to the reefs and follow it down into the foot wall and up into the hanging wall we do not find any particular changes setting in at the beginning or ceasing of the reef-formation. And the reefs lie, as pointed out before, on different levels, so it has obviously been a mere chance where and when they have developed.

The start of the reef often takes place contemporaneously from the whole surface covered by the reef. The corals have not for their development needed any firm ground, for instance in the form of shell banks, conglomerates, etc. They have grown in the calcareous mud, branched themselves and formed coherent masses. As the reef grew higher it was supported by the sediments deposited on its sides. The gap between the branches of the reef-forming organisms has been filled up by calcareous mud, which has hardened and given the reefs strength enough to support the mass increased through the growth.

The Danian reefs sometimes show on their upper surface a slight covering of sulphide of iron, of the same nature as that observed in the Silurian reefs of Gotland as also in the Ordovician reefs of Dalecarlia. Whereever a precipation of sulphide of iron has taken place, it has killed the reef builders. It has not, however, been possible to show the covering of sulphide of iron on the Danian reefs except in some places, and the causes for the ceasing of the reef-building must therefore be searched somewhere else. A stronger deposition of mud seems to me to be the reason. When the corals and other reef builders (on account of want of food?) have not been able to grow as quickly as the calcareous mud accumulated, they have been suffocated in this. Local currents have certainly played an important part here, and they also explain the different stratigraphical appearance of the various reefs.

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[1] Hennig (1899) has discussed the problems closely, according to my opinion, however, without having found a satisfactory solution.

The Character of the Danian Reefs. Comparison with other Fossil and Recent Reefs.

The Danian reefs are coral reefs with hydrocorals and other reef formers. They show great affinity to Tertiary and recent reefs. Contrary to the recent coral reefs, which grow principally on or just under low-tide level, the Danian reefs have been formed entirely in considerably deeper water. The corals belong to genera and forms which in recent seas are found mostly at depths of more than 100 m. The same is the case with the hydrocorals, bryozoans, and crinoids. Also the rocks surrounding the reefs, the hanging wall, the foot wall and the lateral rocks, consist of a material which proves a deposition at a corresponding depth.

Both with regard to the kind of the reef builders and to the milieu of formation the Danian reefs are quite different from other fossil reefs of Sweden.

The Silurian reefs are essentially built up of stromatoporoids, besides corals, bryozoans, and crinoids. Calcareous algae also form part of them. They have been formed in shallow water and as a rule in connection with changes in level.

The Ordovician reefs are above all built up of calcareous algae. These reefs to are shallow-water formations.

Thus the Danian reefs have considerably greater connection with Tertiary and Quaternary reefs than with Paleozoic ones, and they have their nearest recent analogy in coral beds at a depth of 100—300 m.

SUMMARY.

As reef limestones the author has interpreted, investigated and described unstratified masses, built up by calcareous organisms and enclosed in stratified rocks. The Swedish material illustrates three different types of reefs, viz. coral reefs, stromatoporoid reefs and algal reefs.

The *coral reefs* belong to the Danian and are found in southernmost Sweden and in Denmark. They are principally built up of branched corals (*Hexacoralla* and *Alcyonaria*) and hydrocorals. They contain remains of a rich animal life. They have been formed in relatively deep water (more than 100 m). The surrounding stratified sediments consist essentially of bryozoans, foraminifers, coccolites, and fine calcareous mud.

The *stromatoporoid reefs* belong to the Silurian and appear in the island of Gotland. They are mainly constructed of stromatoporoids, corals (*Tetracoralla, Heliolitidae,* and *Tabulata*), and calcareous algae. They have been formed in shallow water (about 10—50 metres) in belts parallel to the coast line. Surrounding stratified rocks are fragment limestones with crinoids, brachiopods, trilobites, ostracods, lamellibranchs, gastropods, calcareous algae, etc.

The *algal reefs* belong to the Upper Ordovician and Lower Silurian. They appear in Central Sweden, in Dalecarlia. The reef-building organisms are scarcely identifiable in the strongly recrystallized limestone, but calcareous algae of Collenia-type are rather common and other types may have contributed still more actively to the reef formation. Corals are found in small quantities. The reefs have been formed in shallow water at the same time as marls and limestones, rich in crinoids, brachiopods, and trilobites.

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