SVERIGES GEOLOGISKA UNDERSÖKNING

SERIE C NR 736 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 71 NR 11

CARL-OLOF ERIKSSON AND SVEN LAUFELD

PHILIP STRUCTURES IN THE SUBMARINE SILURIAN OF NORTHWEST GOTLAND

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ABSTRACT

Eriksson, C.-O. & Laufeld, S.: Philip structures in the submarine Silurian of northwest Gotland. Manuscript delivered 12th May, 1977.

The Silurian succession of the northwest coast of the island of Gotland includes the Lower and Upper Visby Beds and the Högklint Beds. Aerial photographs have revealed the occurrence of 108 concentric and semicircular structures — between 10 and 80 m wide — in the submarine wave-cut platform outside the cliff. The structures were caused by the sagging of Högklint reefs of *Cyrtograptus murchisoni* Zone, i.e. earliest Wenlockian, age into the semiconsolidated Visby Beds. A structure of this kind is named "Philip structure", which is defined as "a circular or ellipsoidal depression beneath and caused by a reef or bioherm". The new term "Cumings structure" is introduced for "a circular or ellipsoidal domelike structure consisting of the quaquaversally dipping beds immediately overlying and adjacent to a reef or bioherm". Maps show the geographical distribution of the 108 Philip structures encountered and their relation to the Högklint reefs exposed in the supramarine rocks. The palaeogeography of the Högklint reefs is discussed and it is concluded that the submarine Philip structures represent the landward part of a 2—3 km wide zone of comparatively small subcircular reefs located leeward of a string of fairly large reefs that were elongated along, and grew parallel with, the coast in Högklint time.

PREFACE

When the junior author visited Gotland in the spring of 1973, Arne Philip — architect, photographer, aviator, and geologist — of Visby showed him a great number of aerial photographs of the Isle of Gotland taken from a small fixed-wing aircraft at low altitudes. Philip demonstrated several interesting geological structures on his photographs and asked about the probable nature of some of these. At least two kinds of features in the Silurian bed-rock were not recorded on Gotland earlier and, as far as we are aware, the concentric depression structures described in this publication and named ***Philip structures*** in honour of their discoverer are nowhere as well developed as on Gotland.

At the time of Philip's discovery of the concentric structures in the shallow sea immediately outside the northwest coast of Gotland, it was only possible to speculate on their origin. The most probable explanation, however, was one that involved differential compaction of the bedded sediments adjacent and subjacent to the massive reef bodies in the uppermost Llandoverian—lowermost Wenlockian of Gotland. Because the junior author suspected that the concentric structures could be used for a reconstruction of a hitherto unknown string of reefs northwest of, but contemporaneous with, the Högklint reefs that nowadays are exposed in the cliff along the coast, he suggested to the senior author to make a detailed analysis of these structures as the subject of his Master's thesis. The Geological Survey of Sweden granted financial support for the aerial photographing of the entire cliff and wave-cut platform along the northwest coast of the island. Generously, the Geological Survey also defrayed the costs of the senior author's field work.

In August 1973, Arne Philip shot more than 1500 aerial photographs which the senior author mounted in strips to produce a composite image of the entire coastal area. Following identification and delineation of all concentric structures discernible on the photographs, the location of each structure was marked on the topographical and economical map sheets. The field work was done in the late autumn of 1973 and several times under adverse weather conditions such that the senior author once escaped from drowning only by luck.

Later, Arne Philip shot a new series of photographs in colour and black and white of some of the more conspicuous concentric structures, partly for educational purposes, partly for evaluating various films in connection with work on other structures in the shallow waters visible from the air. Some of this later work was partly paid for by grant to the junior author from the Royal Swedish Academy of Science. Some of these photographs of the Philip structures have been used by us in lectures given in Scandinavia and North America and by A. Martinsson (1975). Further, Arne Philip used some of them as a part of his magnificent photo exhibition "Gotland in bird's eye view" that was on display in Sweden and in the UNESCO-house in Paris (1974—75).

INTRODUCTION

Gotland is situated in the Baltic about 100 km east of the mainland of Sweden (Fig. 1). Silurian marine sedimentary rocks of latest Llandoverian through Ludlovian age form the supramarine bedrock of the island. The strike of the Silurian strata is roughly northeast-southwest and the general dip is about 0.25 degree towards the southeast. Hence, the oldest rocks are exposed along the northwest coast of the island and the youngest in the southeast and south. The Silurian System is underlain disconformably by a sequence of marine Ordovician limestones, shales and subordinate siltstones of a total thickness of 75—100 m. The Ordovician-Silurian boundary is situated about 150 m below sea level at the northwest coast and about 500 m below sea level in the Holmhällar—Hammarshagehällar area in the extreme southeast of the island.

The Silurian of Gotland was subdivided into 13 major topostratigraphic units by Hede (1921, 1925). The chronostratigraphic framework of these units, their thicknesses and main lithologies are compiled in Fig. 2. For elaborate discussions of the local stratigraphy and correlations, reference is made to Hede (1958, 1960), Martinsson (1967), Laufeld (1974a), and Laufeld and Jeppson (1976, Fig. 4).

With a slight overgeneralization it can be stated that the Silurian bed-rock on Gotland consists of three rock types, viz. limestone, calcareous mudstone and subordinate sandstone (Fig. 1). The various types of bedded and reef limestones are comparatively resistant to weathering and erosion and form the topographically high areas on the island. All parts of Gotland 40 metres or more above sea level are located in areas where the bed-rock consists of limestones (Munthe 1913:8). The topographically low parts of the island are, by and large, underlain by calcareous mudstones and shales. As may be gathered from the map, Fig. 1, the main topostratigraphic units cut across the boundaries between the two major rock types.

The soil cover in the topographically high limestone areas is very thin or missing, because the limestones are pure and contain only very small amounts of soil-forming clay minerals, and the drainage is very effective, taking place through karst fissures in the limestones. Vegetation is consequently less dense so it is not surprising that the bed-rock structures on Gotland described in earlier literature are confined to the limestone areas. Comparatively few such structures have been described, however, despite the fact that they are both common and widespread in the highest limestone areas. As the structures in the highest limestone areas are unrelated to the structures to be described here, they are not dealt with further in the present paper.

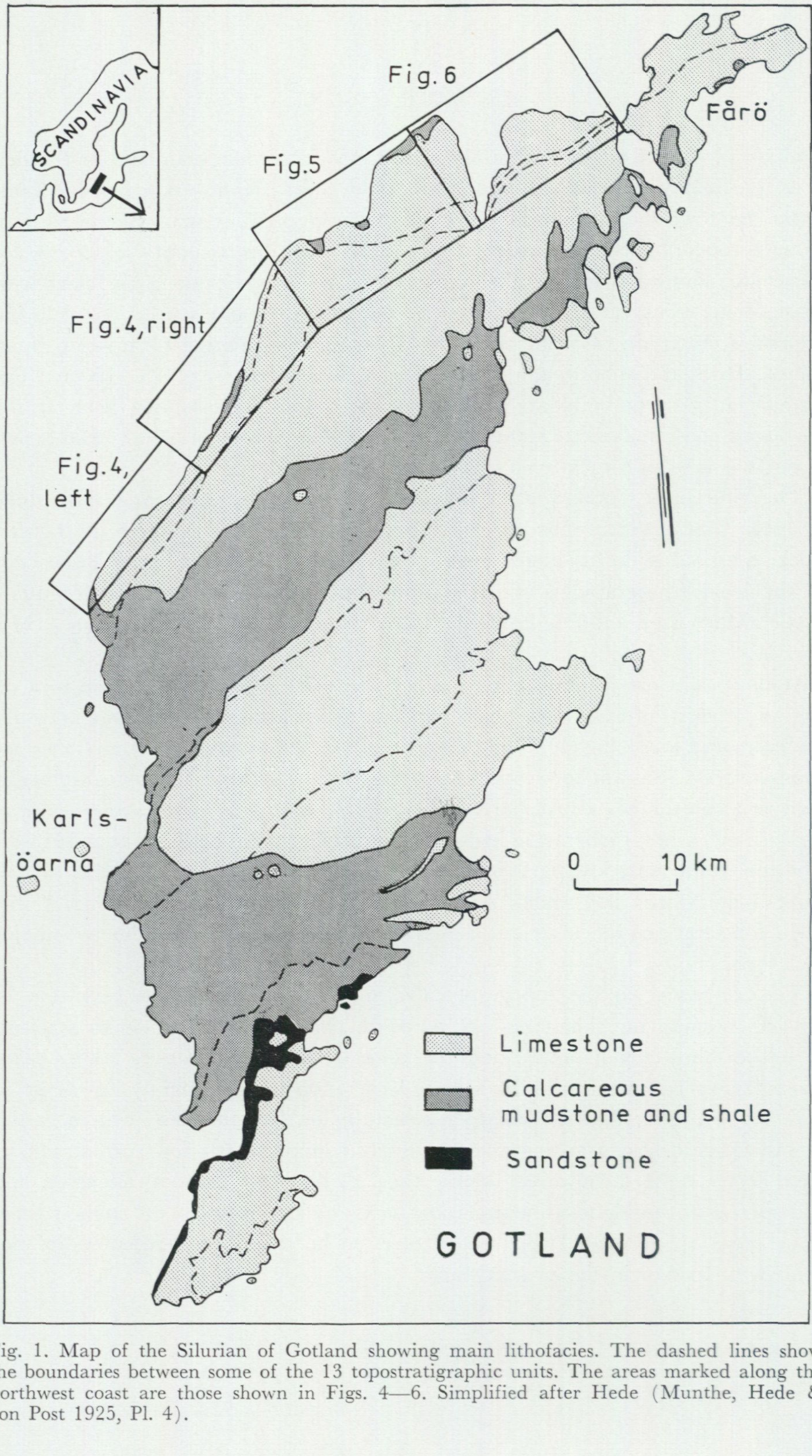

Fig. 1. Map of the Silurian of Gotland showing main lithofacies. The dashed lines show the boundaries between some of the 13 topostratigraphic units. The areas marked along the northwest coast are those shown in Figs. 4—6. Simplified after Hede (Munthe, Hede & von Post 1925, Pl. 4).

GEOLOGY OF THE NORTHWEST COAST

The northwest coast of Gotland is almost entirely a steep cliff coast where the oldest three supramarine Silurian units are exposed. The cliff, which in some places attains a height of 45 m, forms an abrupt transition between the northwesternmost Wenlockian limestone area of Gotland and the Llandoverian, chiefly submarine, area of calcareous mudstones and shales to the northwest. In most places along the northwest coast there is a narrow beach that is paved by beach pebble or gravel, but in a few places the steep cliff plunges directly into the sea. Immediately outside the beach the bed-rock is in many places exposed in a wave-cut platform (*pallen* in Gotlandian) that extends 50—500 m towards the northwest. The water depth increases slowly towards the outer edge of the platform, where it is 3—5 m, then very rapidly so that the edge in some areas forms the uppermost part of a small but fairly steep submarine cliff. There are very few islets and skerries along the northwest coast of Gotland. Accordingly, the coast is exposed to waves that break at the edge of the submarine platform thus abrading the local bed-rock and extending the platform.

The three topostratigraphic units exposed in the cliff and wavecut platform along the northwest coast are, in ascending order, the Lower Visby Beds, Upper Visby Beds and Högklint Beds (Fig. 2).

LUDLOW	WHIT-CLIFFIAN	Sundre Beds	10 m	Bedded limestones. Reef limestones.
		Hamra Beds	40 m	Bedded limestones. Calcareous mudstones. Reef limestones.
		Burgsvik Beds	50 m	Sandstone. Siltstone. Oolite. Reef limestones.
	LEINT-WARDINIAN	Eke Beds	15 m	Bedded limestones. Calcareous mudstones. Reef limestones.
	BRINGEWOODIAN / ELTONIAN	Hemse Beds	100 m	Bedded limestones. Calcareous mudstones. Reef limestones.
WENLOCK	HOMERIAN	Klinteberg Beds	70 m	Bedded limestones. Calcareous mudstones. Reef limestones.
		Mulde Beds	25 m	Bedded limestones. Calcareous mudstones.
		Halla Beds	15 m	Bedded limestones. Calcareous mudstones. Oolite. Reef limestones.
	SHEIN-WOODIAN	Slite Beds	100 m	Bedded limestones. Calcareous mudstones. Reef limestones.
		Tofta Beds	8 m	Bedded limestones.
		Högklint Beds	35 m	Bedded limestones. Calcareous mudstones. Reef limestones.
		Upper Visby Beds	15 m	Calcareous mudstones. Reef limestones.
LLAN.	TELYCHIAN	Lower Visby Beds	9 m	Calcareous mudstones.

Fig. 2. Stratigraphy, maximum thickness and main lithologies of the 13 topostratigraphic units in the Silurian of Gotland. Note the occurrence of reefs or bioherms in all units except for the Lower Visby and Mulde Beds. Simplified from Hede (1960:47—52) and Laufeld & Jeppsson (1976, Fig. 4).

The *Lower Visby Beds* consist of soft, bluish-grey calcareous mudstone (marlstone) intercalated with thin (1—4 cm), often nodular, beds or flat lenses of light grey, argillaceous limestone. Two thin (1—3 cm) bentonite beds are exposed above sea level (Thorslund 1948, Spjeldnæs 1959, Waern 1960, Laufeld & Jeppsson 1976). No reefs or bioherms occur in this unit. The Lower Visby Beds have a maximum thickness of 9 m above sea level but the total thickness of this unit is unknown because its lower boundary has not as yet been defined. The boundary between the Lower Visby Beds and the next overlying unit is undulating. The location of this boundary in relation to the sea level deserves a further discussion, partly since it is of some interest with regard to the concentric structures, partly since its location has been described earlier only in Swedish.

The boundary is close to mean sea level at the fishing village of Hall (close to Halls Huk 1 on the geological map sheet "Kappelshamn" — all locality names followed by a figure are described in detail in the code-name catalogue published by Laufeld 1974b), but farther to the east and northeast it is below sea level (Hede 1933:14). Towards the southwest, 1.1—1.5 km south of Häftingsklint 1 (see Fig. 4—6 for location of the localities), the boundary is located about 2 m a.s.l. but then plunges below sea level about 0.5 km farther south along the coast only to reappear above sea level northwest of the fishing village of Ireviken. At Ireviken 2 the boundary is situated about 8 m a.s.l. (Hede 1933:12) and 2 km northeast of Lickershamn at 9 m a.s.l. (Hede 1921:28; on the geological map sheet Lummelunda). It then disappears below sea level again but reappears at, or up to 1 m above, sea level at Lickershamn 1 (Hede 1940:10, 13). Then it can be followed (though covered intermittently) to the beach immediately southwest of Gustavsvik 1 where it again disappears below sea level. In between the latter localities it is located 3(—4) m a.s.l. at Stuklint (Hede 1921:28), 8 m a.s.l. 1.9 km SSW of the light-house at Stenkyrkehuk (Hede 1940:13) and probably 5—6 m a.s.l. in the Lundsklint—Nyhamn area.

Southwest of Visby the Lower Visby Beds are again exposed, the upper boundary of the unit being at 2.5 m a.s.l. at Fridhem (where the rivulet flows into the sea), at 0.5 m a.s.l. between Buske 1 and Högklint 2, at 3—3.5 m a.s.l. at Rövar Liljas Håla (northeast of Ygne 1) and at 4 m a.s.l. at Stavsklint (on the geological map sheet "Klintehamn"). It then plunges below sea level ca. 1 km further southwest not to reappear (Hede 1921:28, 1927:13, 1940:13). It is evident from the abovementioned figures, that the Lower Visby Beds form the lowermost part of the cliff and the narrow beach in many places along the northwest coast. These beds also form, with very few exceptions, the submarine wave-cut platform all along the coast between Gnisvärd 1 in the southwest and the Kappelshamn Bay in the northeast. The structures to be discussed in this paper are located in the wave-cut platform and thus in the Lower Visby Beds.

The *Upper Visby Beds* are lithologically similar to the next older unit. They differ by having a relatively greater amount of calcium carbonate. The beds of

Fig. 3. Philip structure at Balsklint, the protruding cliff in the lower right corner of the photograph. Another (semicircular) Philip structure can be discerned just outside Balsklint. Note the master joints in the wave-cut platform. Compare with Figs. 8, 9, and 15. Approximate scale 1:1500. Photo Arne Philip 1973-08-17, 12:10 PM. Approved for publication 1975-02-24.

argillaceous limestone increase in thickness upwards in the sequence and become more persistent laterally. The intercalations of calcareous mudstone also become thinner upwards. The Upper Visby Beds are further distinguished from older Silurian beds by the occurrence of reefs. These reefs are smaller than the younger reefs in the Gotland sequence and were referred to as the "Upper Visby type" by Manten (1971:57) when he subdivided the Gotlandian reefs into three types. The average size of the Upper Visby reefs is 3—4 m in diameter and 2—3 m in thickness, the largest being about 15 by 5 m (Manten 1971:95). The reefs are more common (12—18/km) in the cliff southwest of Visby than northeast of the city (40 reefs altogether in the cliff between Visby and Halls Huk) according to Manten (1971:81—82). In the southwest, reef growth started fairly early and reefs occur in the upper two thirds of the Upper Visby Beds, whereas the reefs are progressively younger farther towards the northeast. At Lickershamn the reef growth started comparatively close to the Upper Visby — Högklint boundary (Manten 1971:82). In contrast to the younger Gotlandian reefs, tabulates were the dominant framework builders in the Upper Visby reefs. Stromatoporoids, algae and bryozoans were very subordinate in abundance according to Manten (1971:84—85). The Upper Visby type of reef is stratigraphically restricted to this unit and the shape of these reefs is that of a knoll, lens or an inverted cone (Manten 1971:57).

The maximum thickness of the Upper Visby Beds is about 16 m (Hede 1921: 30) and there are at least three thin (1—3 cm) bentonite beds in this unit (Spjeldnæs 1959, Laufeld & Jeppsson 1976).

The upper part of the cliff is formed by the *Högklint Beds,* which are composed chiefly of limestones. Except for the reef limestones, the Högklint lithologies will not be discussed here and reference is made to Hede (1960:50—51) and Laufeld (1974a:8) for a discussion of lithologies and stratigraphic classification. The Högklint reefs belong to Manten's (1971:115) "Hoburgen type", the shape of which is that of an inverted right-elliptical cone or a very elongate flat lens. Stromatoporoids are the dominant reef builders but calcareous algae, tabulates and rugose corals also contribute to the framework (Hadding 1941:16, Manten 1971:51). The volume of a Högklint reef is 100 to more than 1000 times larger than that of an Upper Visby reef. The average thickness of a Högklint reef is 10—20 m and the average width is 50—200 m. Widths of several hundred

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Figs. 4—6. Map of the northwest coast of Gotland between Gnisvärd 1 and the Fårö Sound. Areas with bed-rock younger than the Högklint Beds (Tofta and Slite Beds) are stippled. The Lower Visby, Upper Visby and Högklint Beds are undifferentiated. Reefs of Högklint age shown in black (chiefly after Hede 1927, 1933, and 1940). Offshore concentric and semicircular Philip structures are shown as filled circles and semicircles, respectively. Scale 1:100 000. After copying the figures can be mounted to one coherent map. The original map (on the scale of 1:50 000), in which each structure carries the number of the aerial photograph on which the structure was recorded, is kept at the Geological Survey of Sweden together with all the aerial photographs.

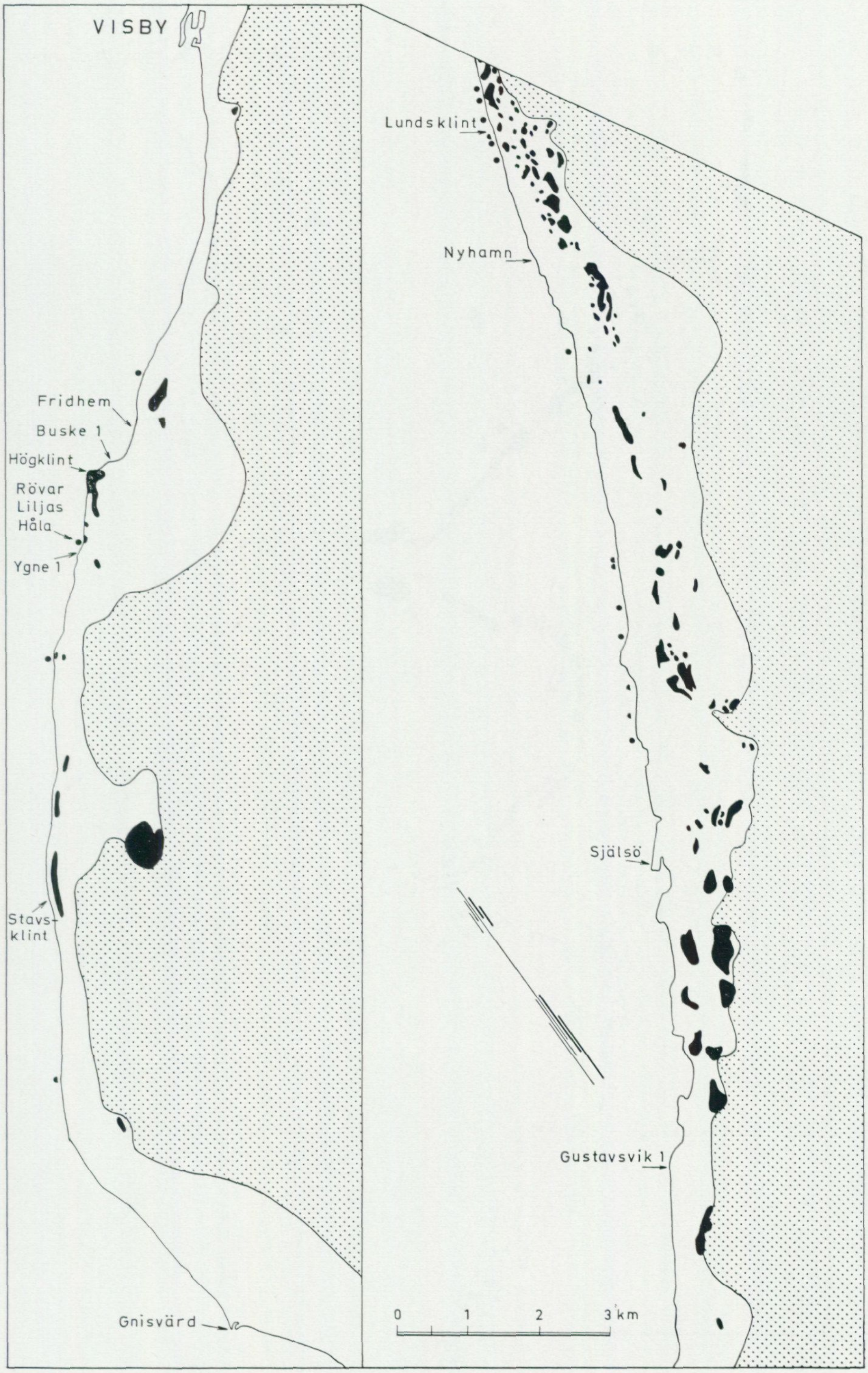
VISBY
Fridhem
Buske 1
Högklint
Rövar
Liljas
Håla
Ygne 1
Stavs-
klint
Gnisvärd
Lundsklint
Nyhamn
Själsö
Gustavsvik 1
0
1
2
3 km

Fig. 4.

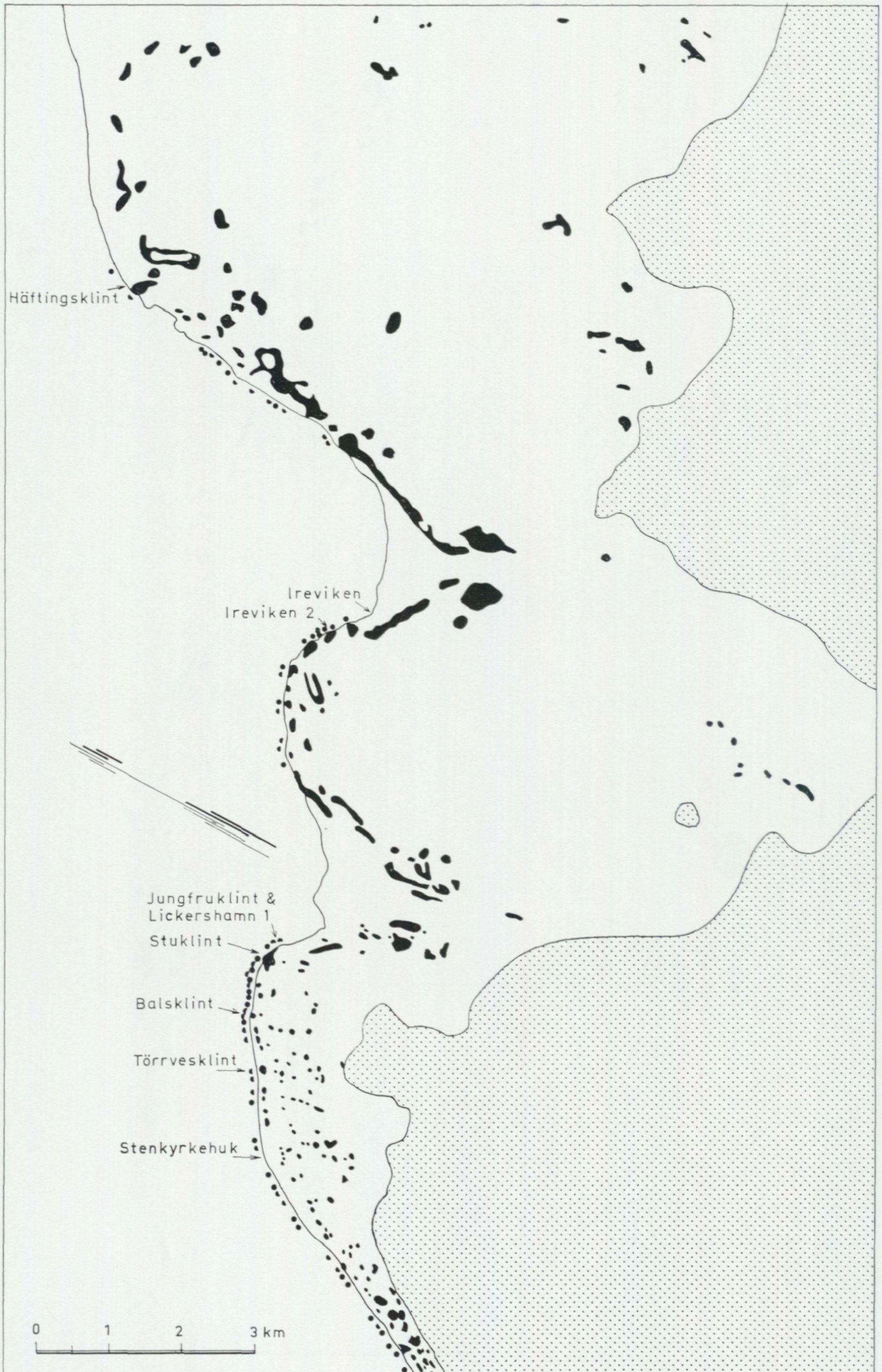
Häftingsklint
Ireviken
Ireviken 2
Jungfruklint &
Lickershamn 1
Stuklint
Balsklint
Törrvesklint
Stenkyrkehuk
0
1
2
3 km

Fig. 5.

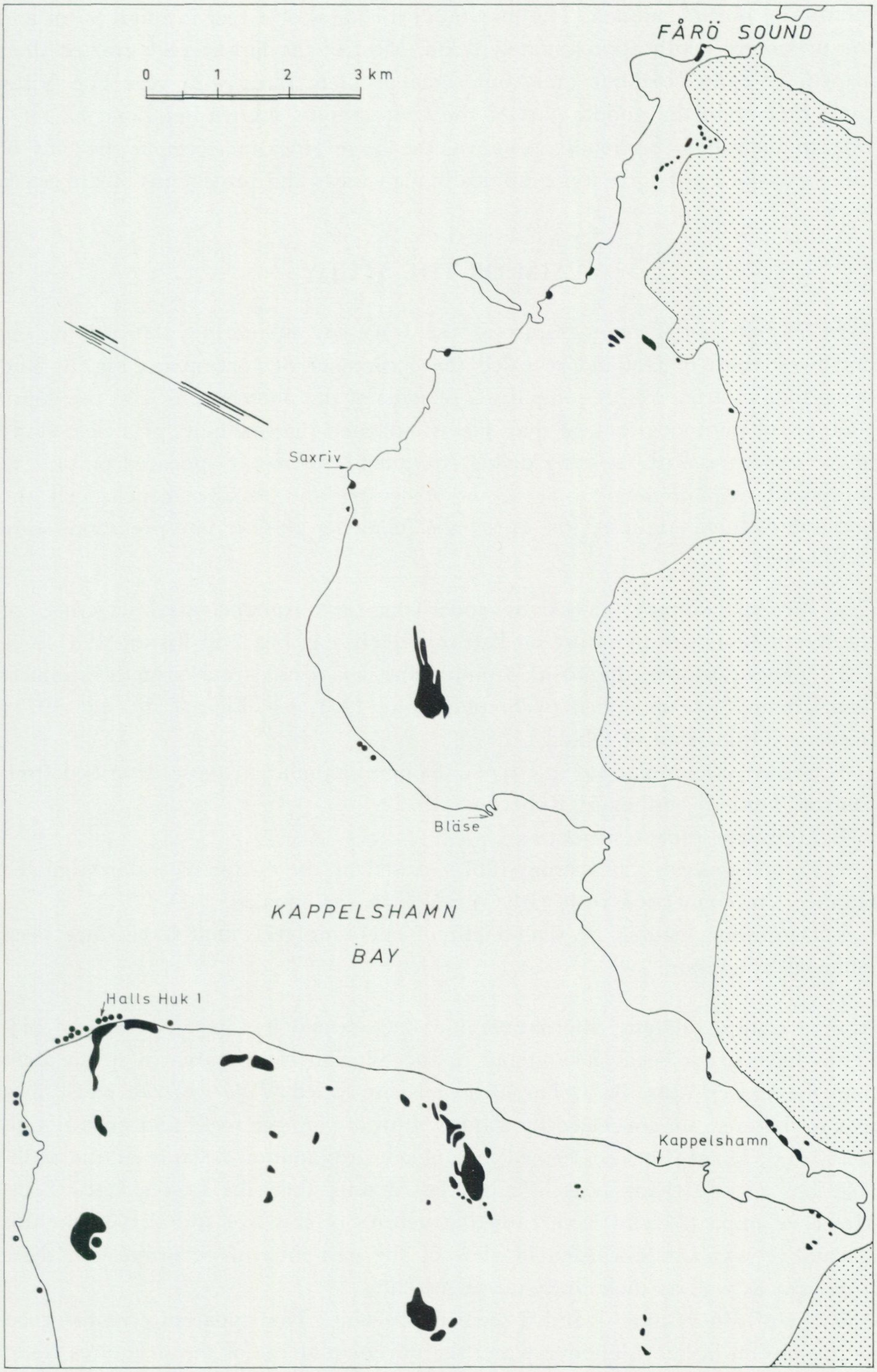
FÅRÖ SOUND
0 1 2 3 km
Saxriv
Bläse
KAPPELSHAMN
BAY
Halls Huk 1
Kappelshamn

Fig. 6.

metres are not uncommon. The maximum thickness of a reef is about 35 m and the maximum width approximately 3 km. Most of the largest reefs started their growth in early Högklint time, but some of them already in very late Visby time, that is, in the middle part of the *Cyrtograptus murchisoni* Zone (Z. 26). Due to their high erosional resistance, the large Högklint reefs in the cliff of the northwest coast form topographically high areas and projections of the coastline.

AIM OF THE STUDY

Arne Philip's aerial photographs of the wave-cut submarine platform of the northwest coast of Gotland revealed the occurrence of concentric (Fig. 3) and semi-circular structures. A comparison of some of the photographs with the depth contours of the topographical map sheets indicated the feasibility of a field study of the structures without using diving equipment. Hence, it appeared possible to study and map in detail some of the structures and to solve conclusively the question of their origin. At the outset the following possible interpretations were considered:

1. Periclinal dipping caused by underlying reefs (quaquaversal structures of the North American literature on Paleozoic reefs, e.g. Fig. 2 in Fenton 1931).
2. Domes caused by diapirism of underlying, less dense strata; structures similar in origin to those described by Stephansson (1971, e.g. Figs. 9, 11, 12; 1972) from the Ordovician of Öland.
3. Growth accumulations in circular bioherms similar to those described from Central Texas by Shumard Roberson (1972).
4. Meteorite-impact structures.
5. Funnel grabens (Lindström 1967) caused by the escape of water from the sediments in connection with early Wenlockian earthquakes.
6. Depressions caused by the weight of overlying reefs that have since been removed by erosion.

After a critical analysis, alternatives 1 and 3 seemed less likely; reefs and bioherms have never been encountered in the Silurian of this area in strata older than the Upper Visby Beds. The Ordovician so-called "*Palaeoporella* reefs" present in the area are concealed by about 150 m of younger rocks and need not be considered. Diapirism also seemed an unlikely explanation because of the probable lack of underlying beds of much less density than the Lower Visby Beds. Meteorite impacts could have caused structures of this size and shape, but this alternative was also discarded in view of the vast area of occurrence of these structures as well as their linear arrangement.

Either of alternatives 5 and 6 seemed probable. The apparently undisturbed sedimentation in late Llandovery and the fairly equal size of the structures could be held against the funnel graben hypothesis. On the other hand, against the hypothesis of reef depressions spoke the fact that the reefs that caused the depressions should have had their initial growth point or apex 10—12 m above the wave-cut platform and the structures in it. Only a field study would single out the correct one of alternatives 5 and 6. Hence, the purpose of this study was to map the location of the concentric and semicircular structures, describe their shape and size, discuss why they are discerned easily in the aerial photographs, and explain their origin. We will introduce a formal term for this kind of structure and discuss briefly the palaeogeography of the Högklint reefs.

METHODS

Arne Philip produced an almost complete photographical documentation of the entire northwestern coast of Gotland in a Cessna 172 aircraft from an altitude of 300—500 m a.s.l. Due to the insurmountable difficulties to keep a constant altitude with a small aircraft in the turbulent air above a high cliff, the scale of the prints used varies between 1:2500 and 1:3200. More than 1500 negatives (24×36 mm, black and white) were taken with 50 % overlap to get a stereo effect. Prints of the size of 8×11.5 cm were mounted with high angular accuracy into strips of about 0.5 m length (7—10 prints). The economical map sheets at the scale of 1:10 000 were used as a reference, because these maps are drawn on aerial photographs. It should be mentioned that no submarine structures can be discerned on the economical map sheets. However, the latest photo maps at the scale of 1:10 000 can be used for plotting the edge of the wave-cut platform as well as the locations of all major structures on the platform. In addition to the low flight altitude one of the secrets behind Arne Philip's outstanding aerial photographs from Gotland and elsewhere is that he is flying early in the morning or late in the afternoon when the sun rays hit the earth's surface very obliquely and produce the shadows necessary for a sharp and detailed image.

Structures were identified and marked on the strips as were those objects that were considered useful as reference points in the subsequent field study. The locations of all structures marked on the strips were then plotted on the topographical map sheets at the scale of 1:50 000 to get an overall picture of the geographical distribution of the structures. In this way, 75 concentric and 33 semicircular structures were recorded on the strips of photographs (Figs. 4—6) between Gnisvärd 1 in the southwest and the Fårö Sound in the northeast. No structures were recorded west and north of the Isle of Fårö.

Most of the fieldwork was carried out in chest waders in the fairly shallow water that covers the majority of the structures. The aerial photographs are a necessary aid in field work on the wave-cut platform, since they show a great number of boulders that have to be used for orientation. Boulders exposed above the water surface are the most useful ones. The sea-bed was studied by using a face mask. As the water depth did not allow the use of a standard compass in the crucial measurements of dip of the strata that form the concentric structures, a special dip measuring device was constructed (Fig. 7). By using this jointed wooden parallel trapezium, which has a sensitive level mounted on its uppermost part that is kept above the water, dips as small as 0.5° can be recorded.

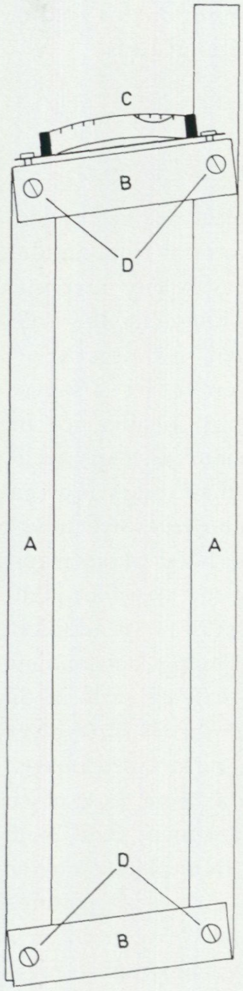

Fig. 7. Dipmeter constructed by Carl-Olof Eriksson for measurements below sea level. A = Parallel wooden rails 160x3x2 cm and 135x3x2 cm, respectively. B = Parallel wooden rails 28x7x3 cm. C = Ruled level with adjusting screws. D = Movable joints of countersunk bolts, plates and nuts. Strike is measured with a standard compass at the upper B, provided that the metal parts are non-magnetic.

THE PHILIP STRUCTURES

The beds that form the uppermost part of the wave-cut platform are lithologically very similar to the supramarine part of the Lower Visby Beds. They differ only by containing a few beds of argillaceous limestones that are thicker (5—30 cm) and laterally much more persistent than those of the supramarine sequence. In several areas with concentric structures, the surface of the wave cut platform consists of a 20—40 cm thick, slightly undulating bed of argillaceous limestone that is swept free of loose material by the surf. On top of the thick limestone bed at, for instance, Balklint (Figs. 8—9) and Jungfruklint there are perfectly displayed concentric structures that were studied in detail. The concentric structure at Balsklint is ca. 80 m in diameter and its centre is located about 1 m above the thick bed of limestone at its periphery. Its construction can be compared with a stack of plates with successively smaller plates upwards. In the concentric structure the plates have their counterparts in beds of argillaceous limestone. The area between the margins of successive plates is formed by the soft calcareous mudstone (marl) between the limestone beds. At Balsklint the beds of argillaceous limestone are 1—40 cm thick and the argillaceous intercalations 1—4 cm. All beds dip towards the centre of the structure with the amount of the dip at Balsklint varying between 0.5° and 6°. At this locality it is especially easy to realize why the concentric pattern is so conspicuous on the air photographs. Obviously the prime reason for this is the fact that the upper part of the peripheral cuesta of each limestone bed carries growing seaweed and algae that is fairly dark, whereas the caved parts of the structure, where the soft marl crops out, are filled by light-coloured fine sand. A schematic cross section of a concentric structure is seen in Fig. 10.

Of the 75 concentric structures identified on the aerial photographs, 48 were studied in the field. The diameter of these structures varies between 10 and 80 m and their central part is situated between 0.5 and 1 m above the surrounding sea-bed at their periphery. The limestone beds in these structures dip 0.5—3° towards the centre in all structures except for that at Balsklint, where an extreme value of 6° was recorded. Eccentricity in the structures was never encountered. Some structures, however, are not perfectly circular and a few are ellipsoidal.

The semicircular structures, which provided the definitive explanation of the origin of all these depressional structures, are all located very close to the cliff. Most of them are partly covered by loose rock material and are fairly difficult to see either on the air photographs or in the field. The semicircular structures are similar in size and shape to one half of the concentric ones and evidently, the two were formed in an identical way. At a few places, e.g. Törrvesklint, the beach below the cliff is narrow enough for an inspection of the relationship between a semicircular structure and a reef still in original position in the cliff. Erosion has cut away half of the reef and an aerial photograph shot at an oblique angle (Fig. 11) shows the initial growth point or apex of this Högklint reef to be located above the very centre of the structure. A later stage in the exposure of a concentric structure is seen on Fig. 12, a photograph from Rövar Liljas Håla. Hence, it can be proved that the concentric and semicircular structures were formed below and by fairly large reefs of Högklint age.

Fig. 8. Drawing of the submarine Philip structure at Balsklint based on the photograph in Fig. 9. The beach at the lower edge of the picture is stippled. The hatched area in the upper part is located outside the edge of the wave-cut platform and more than 3 m below the surface of the platform.

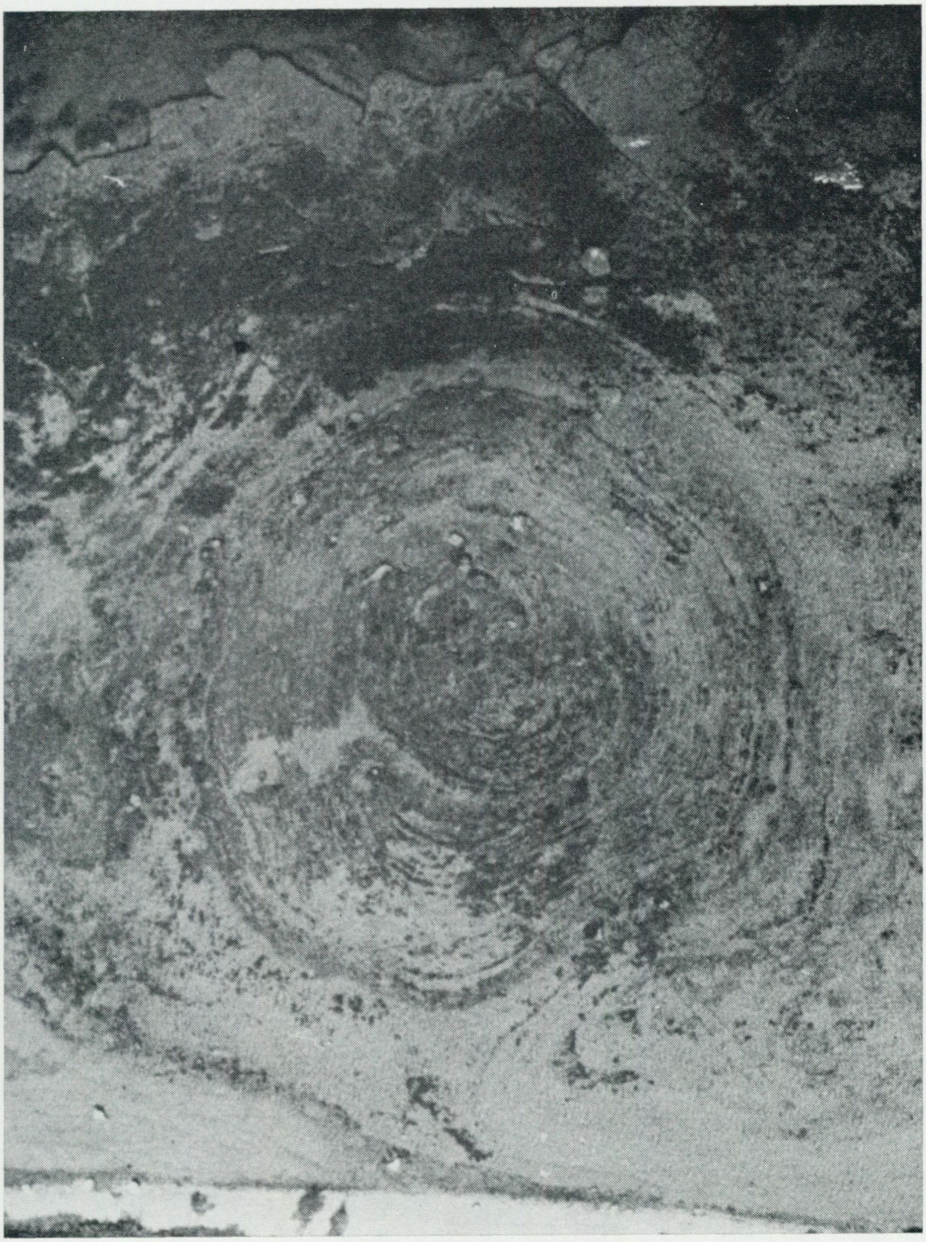

Fig. 9. Photograph of the Philip structure at Balsklint. Compare with Fig. 8 in the same scale, approximately 1:750. Note the boulders that can be used for orientation on visits to the locality. Photo Arne Philip 1973-08-17, 12:10 PM. Approved for publication 1975-02-24.

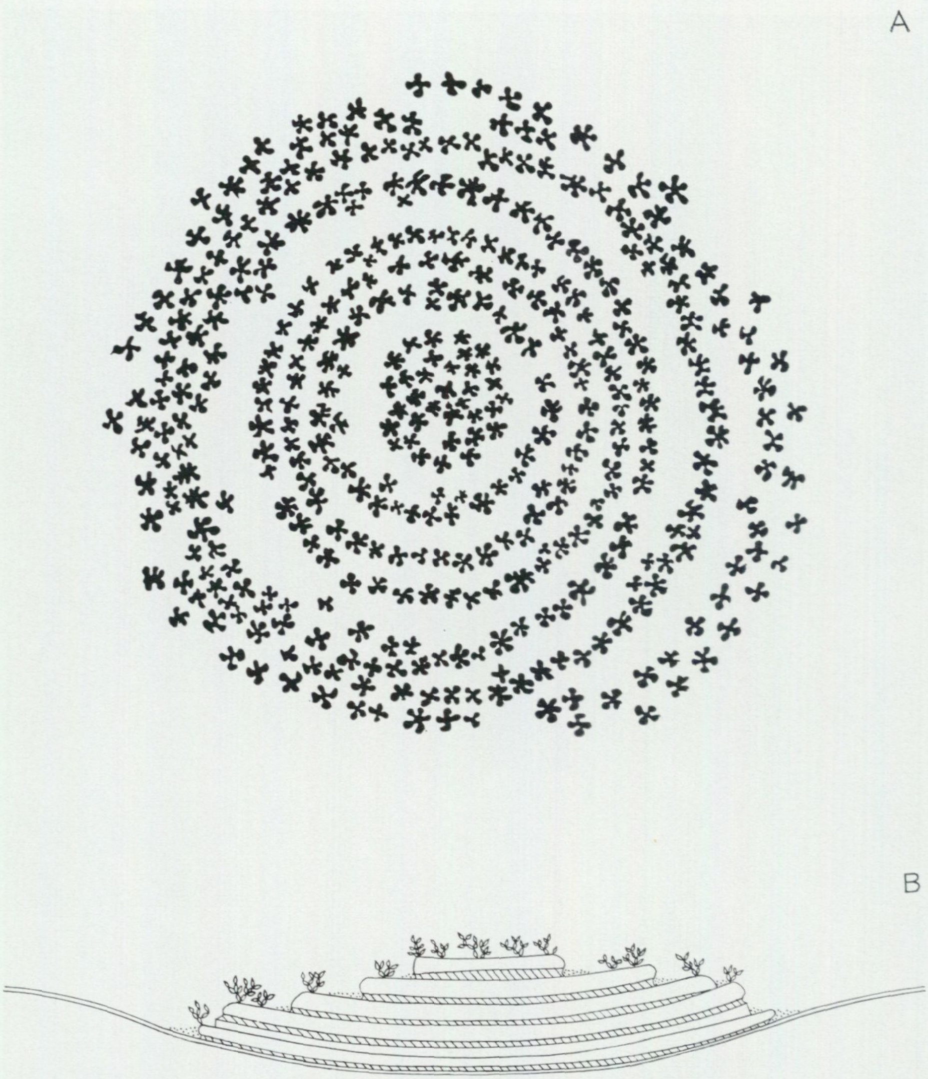

Fig. 10. Schematic drawings showing the construction of a Philip structure in the wave-cut platform at the northwest coast of Gotland. A = View from above with the concentric strings of seaweed growing on the cuestas. B = Section showing the relatively thick limestone beds carrying seaweed at their edges. The marly intercalations (hatched) have been eroded and caved below the overlying limestone cuestas. Light sand (stippled) contrasts with the dark seaweed. Vertical scale exaggerated.

As far as we know, structures of this origin are nowhere as well displayed as along the northwest coast of Gotland. Neither have structures of this kind been documented in the reef literature, even though it has been observed for a long time that strata beneath reefs and bioherms are depressed. It would be convenient to have a separate term for structures of this kind, irrespective of whether they

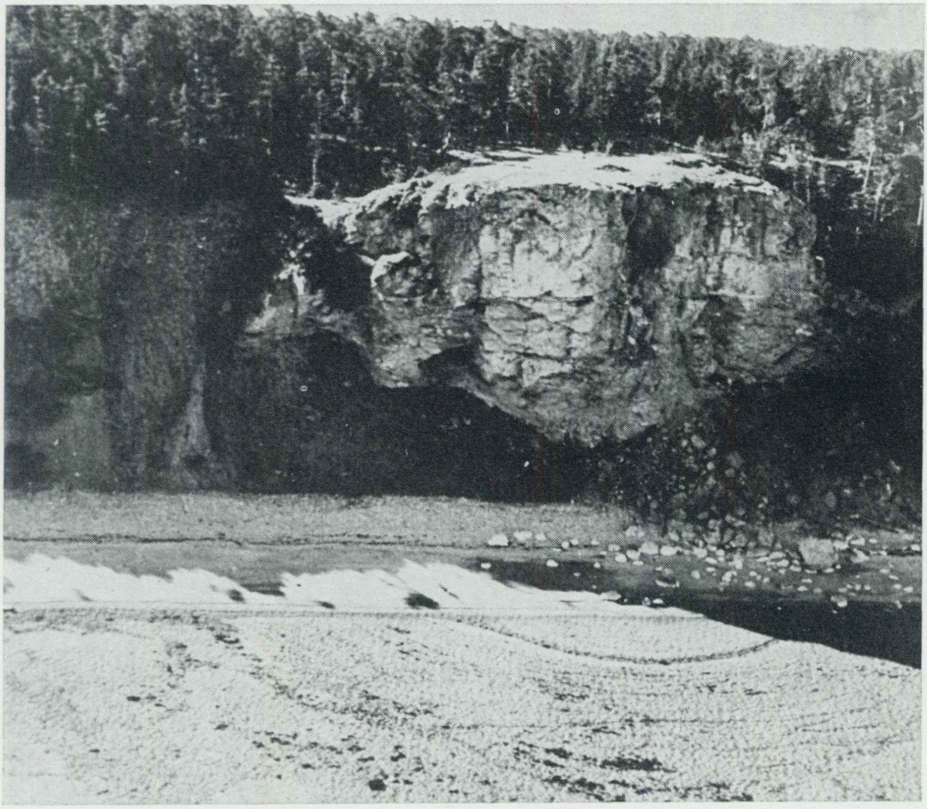

Fig. 11. Aerial photograph of the semicircular Philip structure at Törrvesklint. The northwest (seaward) half of the reef in the cliff has been cut away by erosion and the center of the Philip structure coincides exactly with the lowermost growth point (apex) of the reef. Photo Arne Philip (negative in colour) 1973-05-04, 7:25 AM. Approved for publication.

are preserved in a circular, semicircular or even ellipsoidal shape. We propose the new term PHILIP STRUCTURE as the denomination of a *circular or ellipsoidal depression beneath, and caused by, a reef or bioherm*. Similarly, we propose the term CUMINGS STRUCTURE as the denomination of *a circular or ellipsoidal dome-like structure consisting of the quaquaversally dipping beds immediately overlying and adjacent to a reef or bioherm*.

A. Philip discovered and documented the structures bearing his name. E. A. Cumings was the first (partly together with R. R. Shrock) who described in detail the classical Wenlock reefs of Indiana in the 1920's and 1930's. In several publications Cumings discussed the structures of quaquaversally dipping beds that bear his name. The best illustration of a Cumings structure that we are aware of is that of a part of the Thornton reef complex outside Chicago published by Fenton (1931, Fig. 2).

Fig. 12. Almost complete Philip structure outside the pseudorauk (= "false" sea stack) at Rövar Liljas Håla. For scale note 2 m long pitprops at the inner part of the beach ridges to the left. Photo Arne Philip 1973-03-30, 10:40 AM. Approved for publication.

REEFS IN THE CLIFF

In connection with the studies of the wave-cut platform and its structures, the dips of the beds beneath the Upper Visby and Högklint reefs in the cliff were scrutinized. All Högklint reefs that form resistant and protruding parts in the cliff were marked on the aerial photographs as the first part of an ongoing study of the three-dimensional pattern of the Silurian reefs of Gotland.

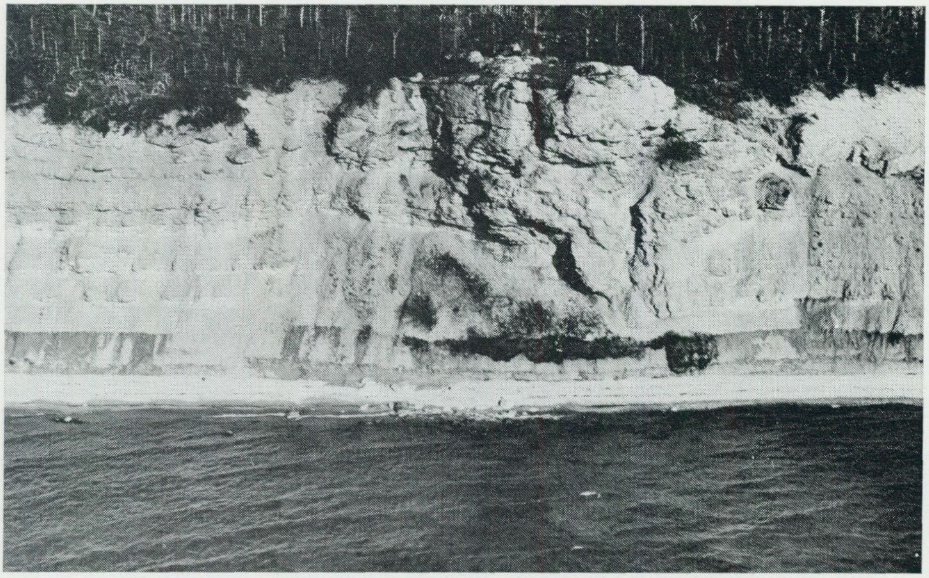

Fig. 13. Oblique aerial photograph of the cliff 350 m north of Lundsklint. Note the sagging of the Högklint reef as evidenced especially by the two bentonite beds in the lower part of the section. In the relatively rainy autumn the bed above a bentonite bed becomes an aquifer and thus a very conspicuous marker bed when the face of the cliff has dried up. Photo Arne Philip 1973-04-27, 4:25 PM. Approved for publication.

Immediately beneath both the Upper Visby and Högklint reefs and bioherms the beds are always more or less buckled down. The Philip structures below the Upper Visby reefs, however, are very small and the dip deviations cannot be traced down farther than a couple of metres below the apex of the reef. Beneath the much larger Högklint reefs the local dips beneath the apex are up to 15°. The dip decreases downwards fairly rapidly, and it would be almost impossible to record the dips of the beds in the lower part of the cliff without using the bentonite beds in the Upper and Lower Visby Beds. The field study was made in the autumn when the top surfaces of the bentonite beds are good aquifers that contrast with the light colour of the dry parts of the sequence (Fig. 13). In all places where scree does not cover the strata in the lower part of the cliff, a Philip structure below a Högklint reef can be traced to the base of the cliff, where the dip is about the same as that of the Philip structure in the wave-cut platform. One of the best localities showing this is located 350 m north of Lundsklint (Fig. 13).

Accordingly, there is reason to conclude that the Philip structures displayed in the wave-cut platform were formed exclusively by Högklint reefs.

FORMATION OF THE STRUCTURES

The Philip structures below the Högklint reefs are synsedimentary and early diagenetic in age. Evidently, the weight of the reef rock increased enough to overcome the strength of the semiconsolidated upper part of the Upper Visby Beds that formed the strata immediately underlying the sea bed at that time. This caused plastic deformation of the sediment layers just below the sea bed. The process continued for a fairly long time and at a smaller pace than the reef building organisms secreted calcium carbonate. It is interesting to note that beds at least 15—20 m, possibly 25—30 m, below the early Wenlockian sea bed were only semiconsolidated. This process of deformation is also a strong argument against the view the the Högklint reefs are not true reefs (*sensu* Ladd 1944), that is, potentially wave resistant structures, but only bioherms or mounds that did not elevate much from the level bottom of the early Wenlock sea. When the sagging of a Högklint reef took place, the process also affected consolidated parts (e.g. fossils with a skeleton of calcium carbonate) of the semiconsolidated beds adjacent to the reef and especially beneath it. A great number of these fossils were thus reorientated from their original growth position. Ruptural deformation of the beds immediately beneath the apex of the reefs is not uncommon. Fossils were fragmented and slickensides formed in the limestones, but the displacements are small. Ruptural deformation of the reef rock itself also took place, chiefly at very early and very late stages of reef growth. Commonly the lowermost part of these reefs, shaped like an inverted cone, is fractured but healed by sparry calcite. The rapidly expanding (mushroomlike) uppermost part of several large Högklint reefs is often so fractured that the reef rock looks almost conglomeratic. All these features are easily comprehended when sagging and differential compaction are taken into consideration.

Evidently, the sagging of the Högklint reefs greatly affected the porosity and permeability of adjacent beds and thus played an important role in diagenesis, especially of the underlying Upper and Lower Visby Beds. An analysis of these factors is beyond the scope of the present paper, however.

The topographical expression of the Philip structures in the wave cut platform is of very late date. As pointed out earlier, the Philip structures are being exposed by erosion now. Rudberg (1967:296—297) demonstrated that present-day erosion of the northwest coast of Gotland takes place at an "average rate" of at least 0.4—0.6 cm per year. Later studies by Rudberg (1976, pers, comm.) have shown that the figures should be adjusted upwards to, say 1 cm per year. As no Philip structures have been recorded farther out than about 200 m northwest of the present cliff we get a maximum value of 20 000 years. However, as pointed out by Rudberg (1967:297), the rate of cliff retreat has probably decreased substantially due to the successive widening of the wave-cut platform, so the abovementioned maximum value has to be considerably reduced. Besides,

STRETCH OF COAST	DISTANCE	●	▲	Σ ●▲	●▲ km
Gnisvärd–Visby	20 km	3	1	4	0:2
Visby–Själsö	8 km	0	0	0	0
Själsö – Nyhamn	9 km	4	2	6	0.7
Nyhamn–Häftingsklint	22 km	47	28	75	3.4
Häftingsklint–Hallshuk	11 km	18	1	19	1.7
Hallshuk–Kappelshamn	7 km	0	0	0	0
Kappelshamn – Bläse	12 km	0	0	0	0
Bläse–Saxriv	6 km	3	1	4	0.7
Saxriv – Fårösund	8 km	0	0	0	0
Σ	103 km	75	33	108	

Fig. 14. The distribution of submarine Philip structures between Gnisvärd 1 and Fårösund.

it seems probable that the wave-cut platform was formed after the maximum transgression of the Littorina sea, dated by Lundqvist (1965:86) at 6000—6500 years BP.

GEOGRAPHICAL DISTRIBUTION

The locations of all submarine Philip structures encountered along the northwest coast of Gotland are plotted in Figs. 4—6. Fig. 1 shows the position of each map area of Figs. 4—6 in a more general context.

The southwesternmost Philip structure recorded is located at Stavsklint (Fig. 4) and the northeasternmost one at Saxriv (Fig. 6). All structures encountered are located where the bedrock of the beach and lowermost part of the cliff consists of Lower or Upper Visby Beds, except for the four structures east of the Kappelshamn Bay, Fig. 6, where the bed-rock is made up of argillaceous Högklint limestone. At a comparison of the four maps (Figs. 4—6) it is evident that the distribution of Philip structures between Stavsklint and Saxriv is very uneven. Fig. 14 shows in a tabular way the distribution of Philip structures per kilometre for all parts of the northwest coast west of the Isle of Fårö. A bias is introduced by the fact that the section of coastline between Hallshuk—Kappelshamn and Kappelshamn—Bläse, and Saxriv—Fårösund with northerly and easterly trends respectively, is completely out of strike as compared with the other parts of the

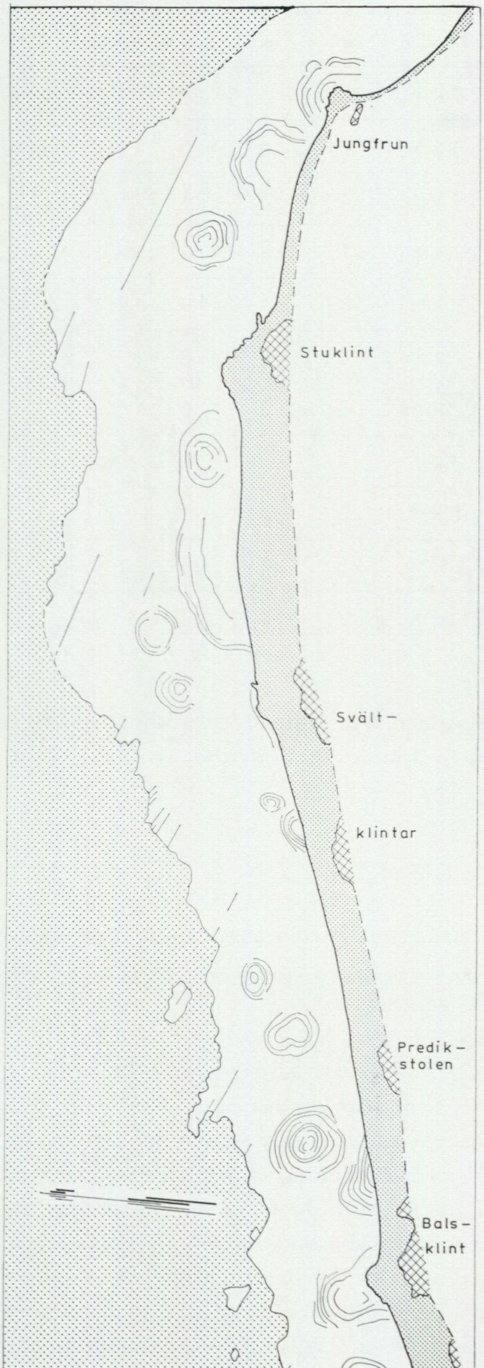

Fig. 15. Philip structures between Balsklint and Jungfruklint. The drawing was made from a strip of aerial photographs. The beach is densely stippled, the Högklint reefs in the cliff are cross-hatched, and the area outside the wave-cut platform is coarsely stippled.

coast. Nevertheless, the distribution of Philip structures is uneven. 87 % of the 108 structures are concentrated within an area that comprises less than 1/3 of the coast line and if the abovementioned parts striking north-south are excluded, within an area comprising between 1/2 and 1/3 of the coast. Along this restricted stretch of coast — between Nyhamn and Halls Huk — there are more than 2.5 Philip structures per kilometre. The part of the coast which has the greatest concentration of structures is situated between Lunds Klint and Lickershamn (uppermost part of Fig. 4 and lower 1/3 of Fig. 5). Within that area there are altogether 45 structures which makes about 5 reefs per kilometre along the strike of the Högklint Beds. Fig. 15 shows the area with the greatest number of structures per kilometre.

Although it cannot be excluded that there are more Philip structures in the fairly restricted areas covered, at the time of our study by Recent sediments, it seems unlikely that such hidden structures are plentiful. Hence, uneven distribution of Philip structures along the northwest coast to a great extent reflects the original distribution of reefs in the Silurian sea during Högklint time.

PALAEOGEOGRAPHY

A study of the geological map sheets (Hede 1927, 1933, 1940) reveals that there are about 425 Högklint reefs exposed at the surface of Gotland. To that figure should be added the 108 reefs revealed by the present study, which altogether makes about 530 known reefs. The scale of Fig. 16 does not allow the plotting of all these reefs (see, however, Figs. 4—6) along about 80 km of the Silurian shelf in Högklint time. Unfortunately, we can only speculate about possible Högklint reefs southwest of the present island. It seems probable, however, that only few and scattered Högklint reefs grew southwest of the supramarine exposures of the Högklint Beds and that reefs — if they existed — did not grow more than a few tens of kilometres towards the south-southwest of Gotland.

Evidence of Högklint reefs east-northeast of Gotland (Isle of Fårö) is also lacking at the present time, but it is probable that reefs grew along the coast in that direction, even though not farther than about 30—40 km east-northeast of Fårö. It is a reasonable assumption that reefs grew roughly subparallel to the coastline in Högklint time for up to 150 km, and that more (possibly much more) than 60 % of this reef zone crops out on Gotland. As pointed out by Manten (1971:311) the Högklint coast line had a northeastern direction west of Visby but an east-northeastern direction north of Fårö. This means that the present northwest coast of Gotland has a slightly more easterly trend than the coast-line in Högklint time. Hence, the large Högklint reefs on Fårö (see Fig. 16) were located farther from the sea shore than, for instance, the reefs west of Ireviken and Lickershamn. If the younger generation of Högklint reefs (situated very close to the southeastern boundary of the Högklint Beds) is excluded, the following model can be used for an understanding of the Högklint reefs exposed on Gotland. A string of fairly large reefs subparallel to and elongated in the direction of the coast line grew farthest from the shore. Reefs in this position occur on Fårö and in the inland part of the Högklint Beds on northern Gotland. These reefs become less elongated and are more widely separated the farther towards the southwest they are located. In the southwest several of these reefs are covered by the Tofta Beds. Leeward (northwest) of this string of fairly large reefs and in a zone parallel to them grew a very great number of small reefs. The latter have more irregular shapes depending on their location in relation to the passages (channels) between the seaward reefs, but several have a subcircular outline. This zone of small reefs in several areas reached a width of at least 2—3 km and it contained literally thousands of reefs. The reefs exposed in the cliff between, for instance, Häftingsklint and Stenkyrkehuk (see Fig. 5) were located along the landward side of this reef zone, a fact that must be taken into account before paleaoecological conclusions are drawn from the distribution of various groups of fossils in the reefs and adjacent sediments.

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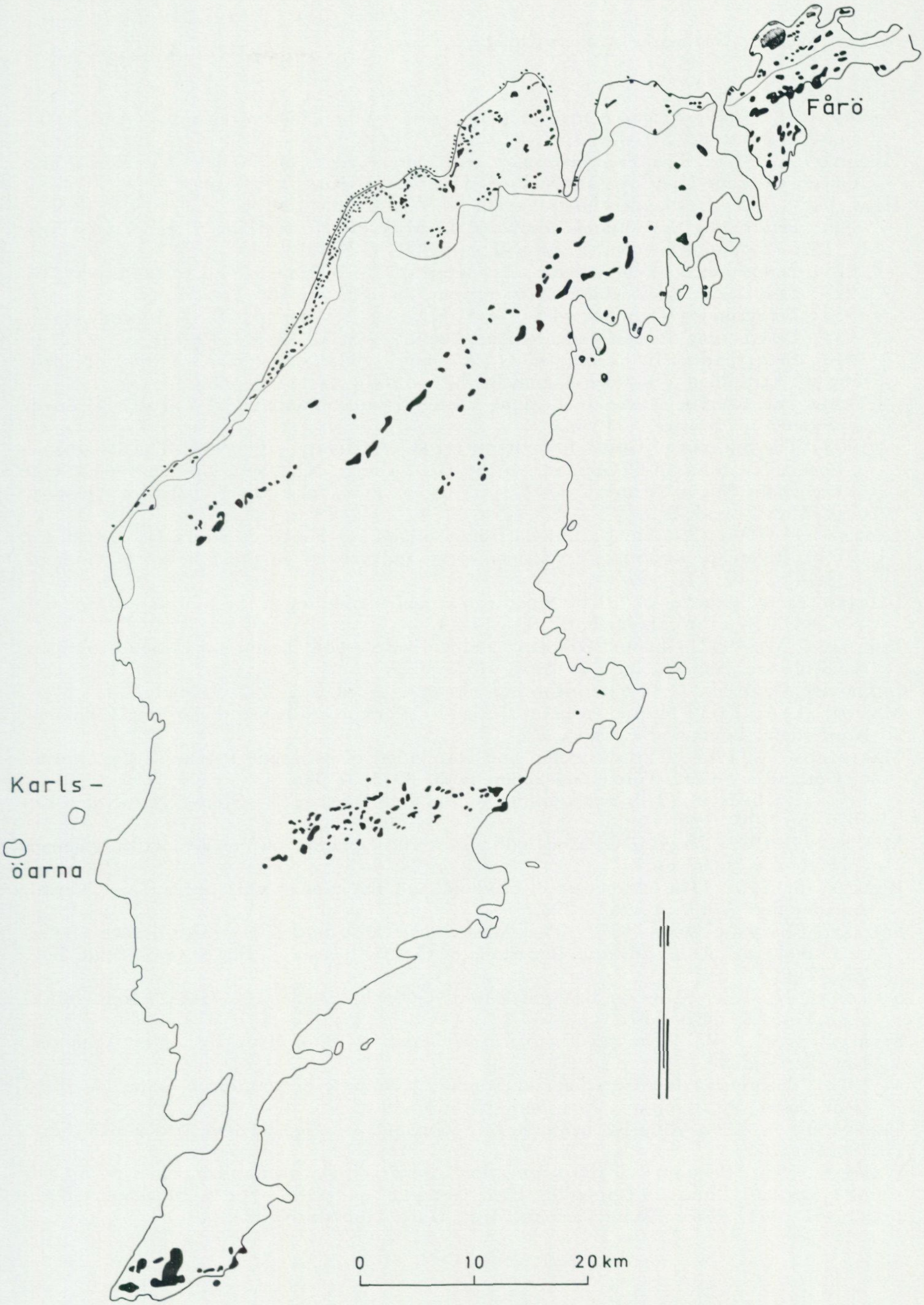
Fig. 16. Map showing the four major belts of Hoburgen and Holmhällar types of reefs in the exposed Silurian of Gotland, from north to south Högklint, Slite, Hemse, and Sundre reefs. The southern three rows according to a map by Hadding (1941, Fig. 6) who compiled them from Hede's and Munthe's geological map sheets. The occurrence of reefs in the Slite, Hemse and Sundre Beds as shown here is much more schematic than that of the Högklint Beds due to the lack of differentiation, in some geological map sheets, between bedded and reef limestones. Hence, a great number of reefs, e.g. those of Stora och Lilla Karlsö, are not shown on the map. The picture of the Högklint reefs is much more complete, even though the large number of subsurface reefs are not shown here. The location and extension of onshore reefs of Högklint age were compiled chiefly from Hede's geological map sheets. Due to the scale of the map, the offshore reefs deduced from the Philip structures are marked schematically only. The boundary between Högklint Beds and younger strata is marked on the map. On the Isle of Fårö the boundary has been displaced slightly towards the southeast to include the outliers of Högklint reefs in the northwesternmost area of the Slite Beds.


Fårö
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