The Silurian Upper Burgsvik and Lower Hamra-Sundre Beds, Gotland

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Five facies are recognized in the Upper Burgsvik and Lower Hamra-Sundre Beds on account of a lithological and paleobiological analysis: I) siliciclastic, II) bioclastic, III) oolitic/pisolitic, IV) oncolitic/biostromal, and V) crinoidal facies. The facies represent five depositional environments: a beach, a fore-shore, a surf, a shallow marine current, and an off-shore environment. The diversity and colony shape of tabulates in facies IV is related to discrete physical and biological factors. The succession of facies reflects a transgressive sequence. Land was situated in the north-west.

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Introduction

The Isle of Gotland in the Baltic Sea is a classic region for the study of Silurian strata. Sedimentary rocks are exposed ranging from the latest Llandovery to the Late Ludlow (Martinsson, 1967). The oldest deposits are found along the north-western coast, the youngest in the south-east. The strata are gently dipping to the south-east. The strike is roughly north-east to south-west, major tectonical disturbances being virtually absent.

This region was situated in Silurian times near the north-western margin of a shallow epicontinental sea in the Baltic syneclise (Schönenberg, 1971). A coast parallel zone of bioherms started to develop during the latest Llandovery. Epeirogenetic movements in the basin caused migration of the reefs towards the south-east. Jux (1957) explained the facies-variation in the Silurian of Gotland by three successive reef zones: 'Visby, Klinteberg and Burgsvik Folgen'. Martinsson (1967) showed weaknesses in Jux' hypothesis on account of the occurrence of ostracod faunas.

Various ideas on the stratigraphy of Gotland have been published since the pioneer study of Murchison (1846). A historical review was given by Manten (1971). We have used a slightly modified version of Hede's stratigraphy (Hede, 1960; Martinsson, 1967; Mori, 1970; Manten, 1971). Laufeld (1974a) presented an inventory of reference localities in the Silurian of Gotland. Three stratigraphical units are exposed in the area under consideration (Fig. 1): the Eke Beds, the Burgsvik Beds and the Hamra-Sundre Beds.

The Eke Beds mainly consist of thin beds of grey, more or less argillaceous limestone, alternating with very thin beds of grey, slightly arenaceous and micaceous marlstone rich in calcareous algae. The calcium carbonate content increases towards the north-east, where the Eke Beds are exposed as stratified grey to light brown-grey, mainly crinoidal limestone, grey to brownish grey marlstone and biohermal limestone (the so-called *Rhizophyllum* limestone in older literature). The thickness of the Eke Beds is about 14 m in borings at Burgsvik (Hede, 1919) and at Grötlingboudd (Laufeld, 1974c). The thickness decreases towards the north-east to 10 m (Hede, 1925).

The Burgsvik Beds consist predominantly of thickly to thinly bedded, light grey, fine grained, slightly calcareous or argillaceous quartz sandstone. Locally, intercalations are found which consist of laminated or very thinly bedded grey, slightly calcareous claystone lenses. The sandstone is mostly overlain by an alternating succession of quartz sandstone and oolite, or ooidal quartz sandstone beds. The lithology of the Upper Burgsvik Beds shows some complicated variations. Consequently correlation is difficult even in closely spaced exposures (Munthe, 1910; Hadding, 1929, 1933; Hede, 1960; Pusch, 1969; Manten, 1971). Correlation of the Upper Burgsvik Beds of the Burgen-Närsholm area with those of the Hoburgen Peninsula is even more complicated because of facies variations and the lack of knowledge of the subsurface geology. The thickness of the Burgsvik Beds in a boring near Burgsvik is 47 m (Hede, 1919). Munthe (1910) and Hede (1925) estimated the thickness of the Burgsvik Beds in the Burgen-Närsholm area at 7 to 8 m, although it is not clear on what evidence this estimation has been based. As

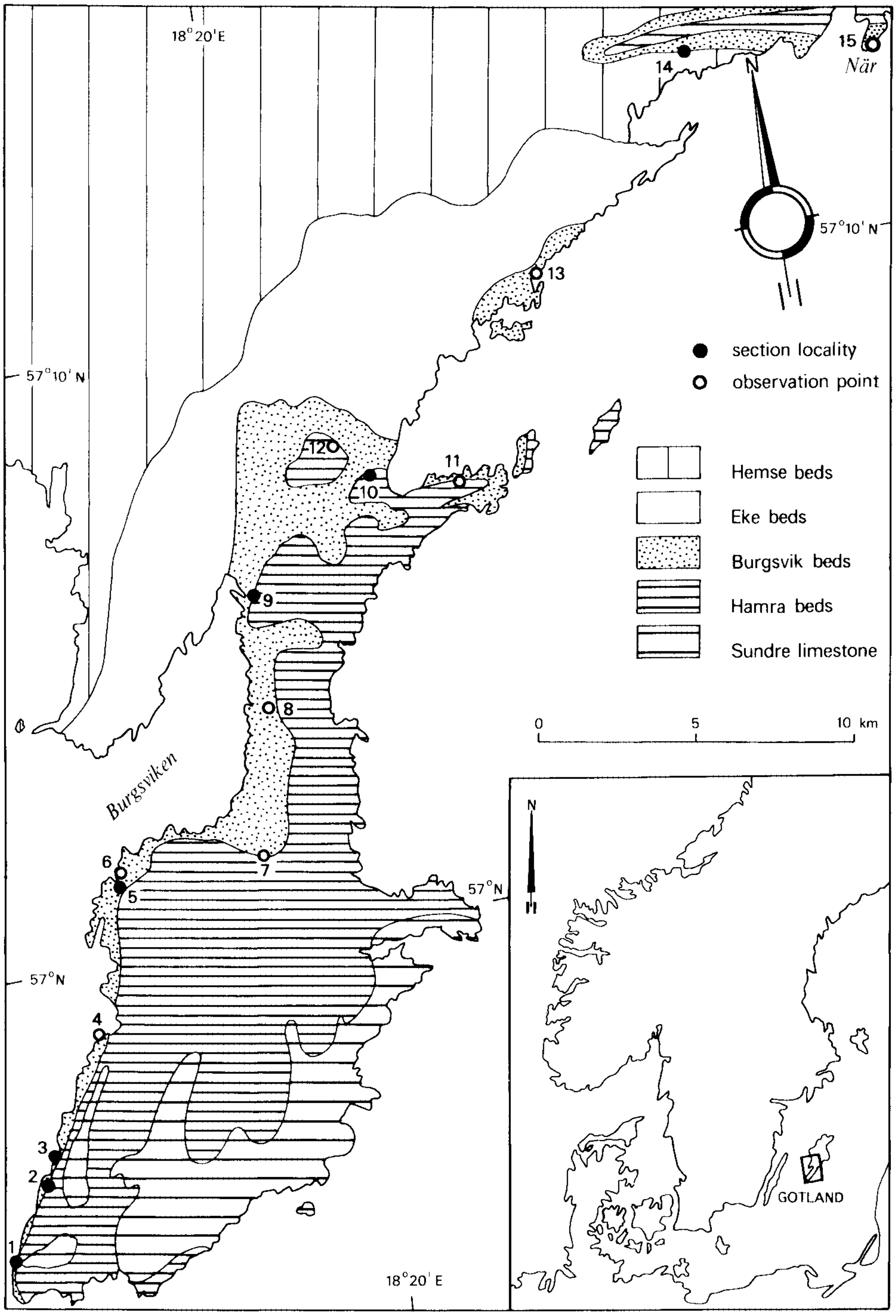

Fig. 1. Geological map of Southern Gotland, showing the localities and codenames of the investigated localities.
1. Hoburgen 2; 2. Husryggen 1, 2, 4; 3. Kättelviken 6, 7; 4. Munkboudd 1; 5. Kulhaken 1; 6. Valar 2; 7. Lajkungsrum 1; 8. Uddvide 1, 2; 9. Fide 1; 10. Rovalds 3; 11. Kauparve 2; 12. Skradarve 1; 13. Ronehamm 1; 14. Burgen 6, 7; 15. Närs Fyr 1, 2.

a result of this the thickness would decrease rapidly from the west towards the north-east.

The Hamra-Sundre Beds have been grouped in one stratigraphical unit by Martinsson (1967), Mori (1970) and Manten (1971), since the lithological subdivision of Hede (1960) is not warranted by the fauna. The beds of the Hoburgen Peninsula consist of a thin basal part with argillaceous, mostly indistinctly stratified grey to light brown algal limestone, which is overlain by a grey to brownish grey, stratified argillaceous limestone, intercalated with grey marlstone. Three distinct facies are found in the upper part. Biohermal limestone (1) surrounded by bedded, mainly crinoidal limestone (2) occurs in the south-west. These two are replaced in the north-east by argillaceous limestone (3), intercalated with marlstone and some fetid limestone with lenses of stromatoporoidal limestone.

The lithology and the paleontology of the transition between the Burgsvik Beds and the Hamra-Sundre Beds is the object of this study. This transition is defined as the unit between the highest massively bedded quartz sandstone of the Burgsvik Beds and the lowest thick crinoidal limestone of the Hamra-Sundre Beds.

Acknowledgements

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The material collected is stored in the Rijksmuseum van Geologie en Mineralogie (National Museum of Geology and Mineralogy), The Netherlands, catalogued under the numbers RGM 243 670 - 243 688.

Lithology

ROCK TYPES

Generally ten rock types can be distinguished between the massively bedded Upper Burgsvik Sandstone and the crinoidal limestones of the Lower Hamra-Sundre Limestone. The limestones are described according to the Dunham (1962) classification.

1) Calcareous quartz sandstone: a fine grained sandstone predominantly composed of quartz grains with 20% calcareous cement.
2) Claystone: thin lenses of dark grey, hardly consolidated clay.
3) Bioclastic quartz grainstone: a lime grainstone composed of various bioclasts with numerous fine quartz grains.

4) Bioclastic oolitic quartz grainstone: like 3 but with a notable amount of ooids.
5) Bioclastic oolitic grainstone: a lime grainstone with on the average equal amounts of bioclasts and ooids.
6) Oolitic quartz grainstone: an oolite with some admixture of quartz grains.
7) Oolitic/pisolitic grainstone: according to grain size an oolite or a pisolite.
8) Oncolitic grainstone: an oncolite with some minor amounts of quartz grains, bioclasts, ooids or pisoids.
9) Poriferan boundstone: an autochtonous reef rock composed of various sponges in life position.
10) Crinoidal grainstone and packstone: a lime grainstone or packstone predominantly composed of crinoid ossicles.

GRAIN TYPES

A mixture of carbonate and non-carbonate grains is found in the Upper Burgsvik and Lower Hamra-Sundre Beds.

Non-carbonate grains – The non-carbonate grains are predominantly composed of quartz with some feldspars and micas. Their grain size distribution in calcareous quartz sandstone was determined after removing the calcite cement. Granulometric analyses were performed by pipetting and sieving the non-carbonate grains from a number of samples. Uniform data were found in most samples. The following Trask's parameters were calculated: median grain size (Md) varies from 0.08 to 0.115 mm, sorting (So) from 1.10 to 1.15. Rounding could not be determined since this was destroyed by the chemical agressive nature of calcite cement with respect to quartz grains.

Carbonate grains – The carbonate grains are composed of bioclasts, ooids, pisoids and oncoids.
Bioclasts — Bioclasts of crinoids, bryozoans, trilobites, corals, brachiopods, ostracods, sponges, bivalves, gastropods, and algae were found in a great variety.
Ooids — Ooids are the diagnostic grain type of the Upper Burgsvik Oolite. An ooid (syn.: oolith) is defined as a small, round (ovate, spherical, or oblate ellipsoidal) accretionary body, resembling the roe of the fish, having diameters of 0.1 to 2.0 mm, usually formed of calcium carbonate in successive concentric layers (cortex) commonly around a nucleus (Gary et al., 1972). An oolite is the sedimentary rock made up chiefly of ooids cemented together. According to the arrangement of the crystals in the concentric layers, the symmetry and the composition or the size of the nucleus, several ooid types can be distinguished in the Upper Burgsvik Oolite. The two basic ooid types are: the radial ooid (a), with the crystals of the cortex arranged predominantly radially, although still showing the concentric structure (Fig. 2a), and the concentric ooid (b), with a predominant concentric structure (Fig. 2b). A transition between these two ooid types is the radial concentric ooid (c), with a radial arrangement around the nucleus and a concentric one in the outer side of the cortex (Fig. 2c and 5a). A deviation from the concentric type is an asymmetrical variety, the excentric ooid (d), with a nucleus outside the centre (Fig. 2d). A grain, resembling an ooid in size and shape composed of fine grained material and lacking internal structure, was called a pseudo-ooid (e) by Cayeux (1935). It is a rare grain type in the Upper Burgsvik Oolite. An abun-

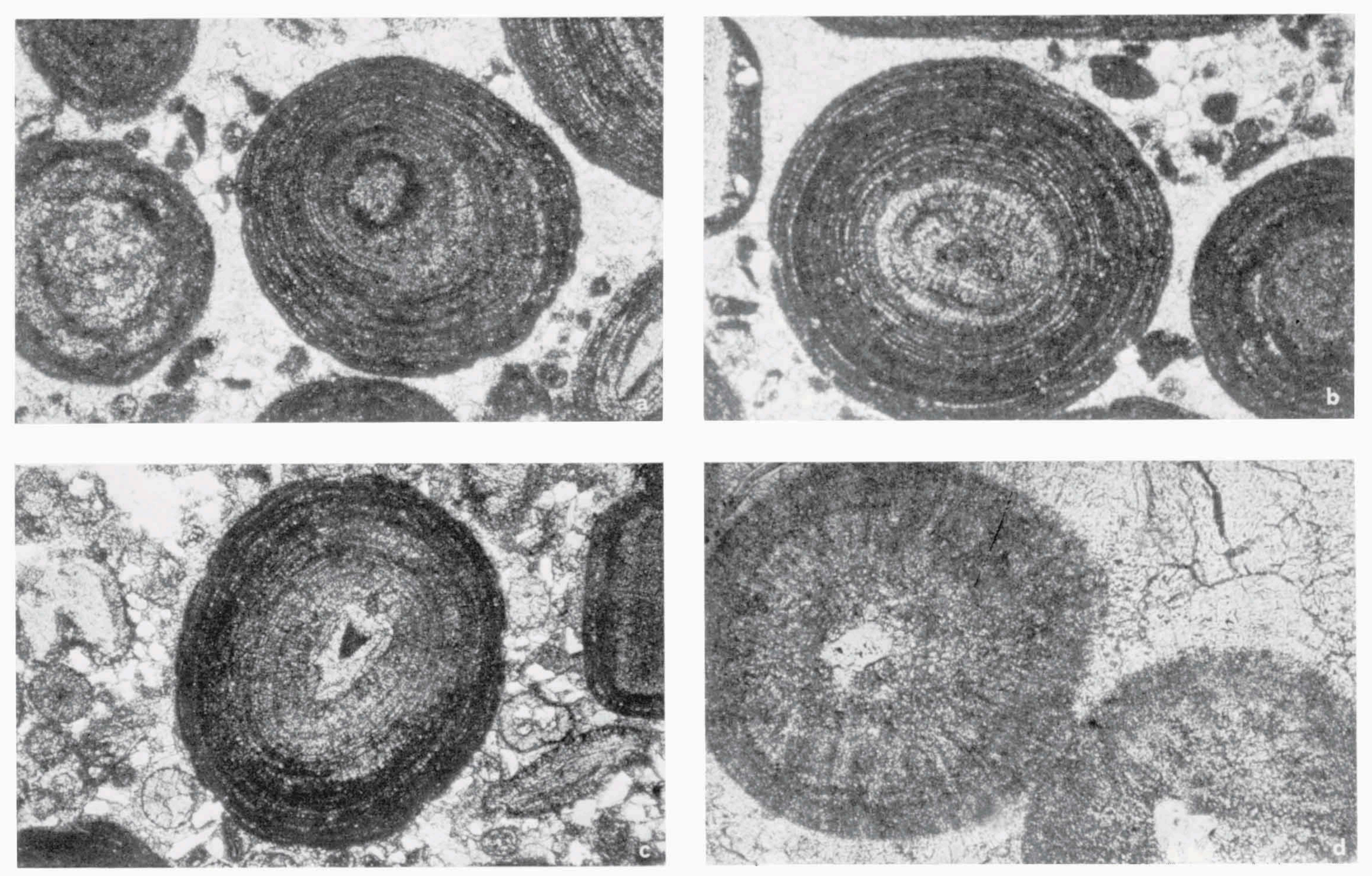


Fig. 2. Ooid types of facies III: a. Radial ooid (variety a), Kulhaken 1, RGM 243 670; b. Concentric ooid (variety b), Valar 2, RGM 243 671. Small neomorphic ooids are found in between the concentric ones; c. Radial-concentric ooid (variety c), Husryggen 2d, RGM 243 672; d. A concentric ooid (variety d), Husryggen 2d, RGM 243 672.

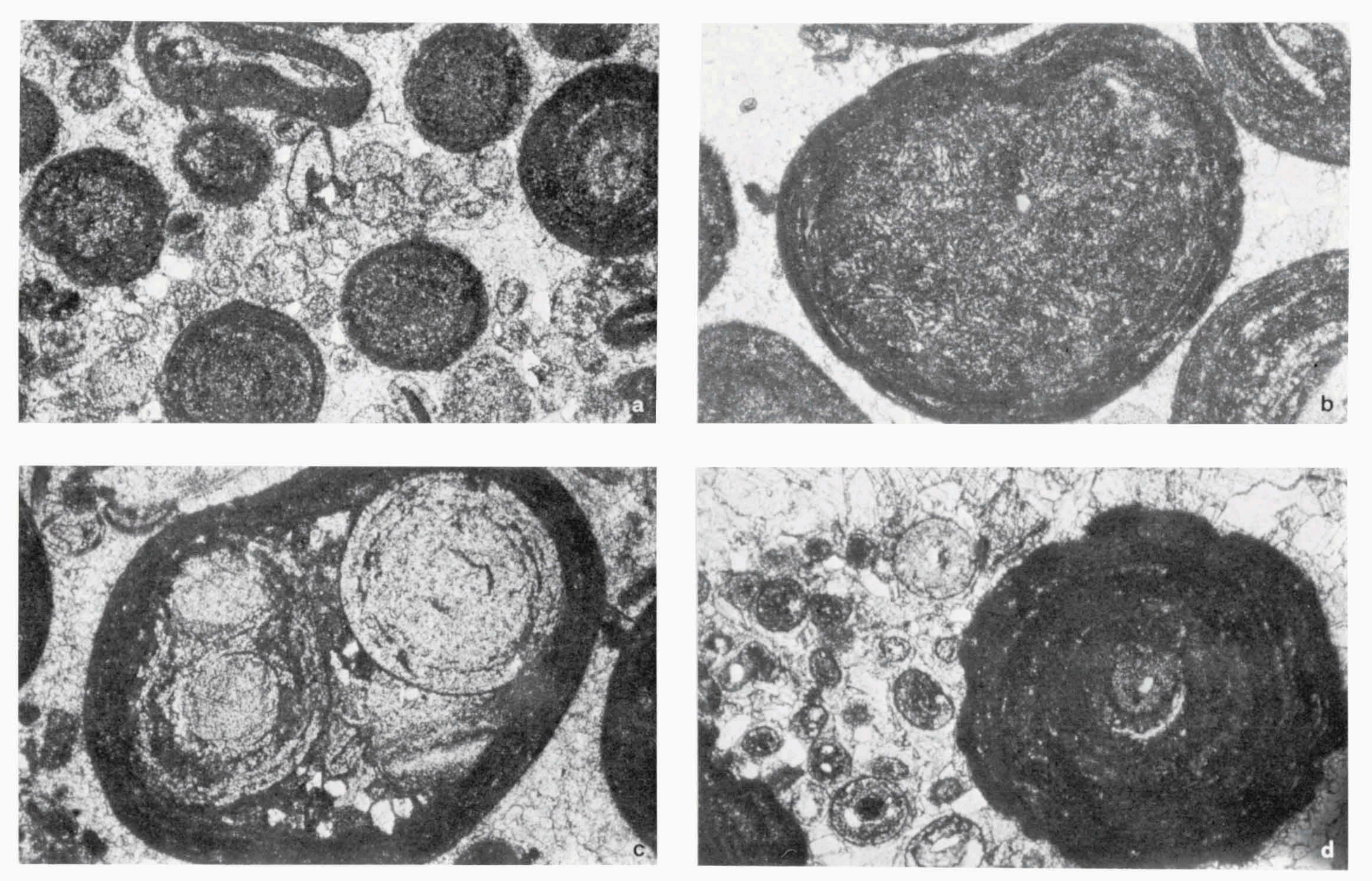


Fig. 3. Ooid types of facies III: a. Pseudo ooid (variety e) and neomorphic ooid (variety f), Uddvide 2, RGM 263 673; b. Coated ooid (variety g), Husryggen 2d, RGM 243 672; c. Composite ooid (variety h), Husryggen 2a, RGM 243 674; d. Lobate ooid (variety i), Kulhaken 1, RGM 243 670.

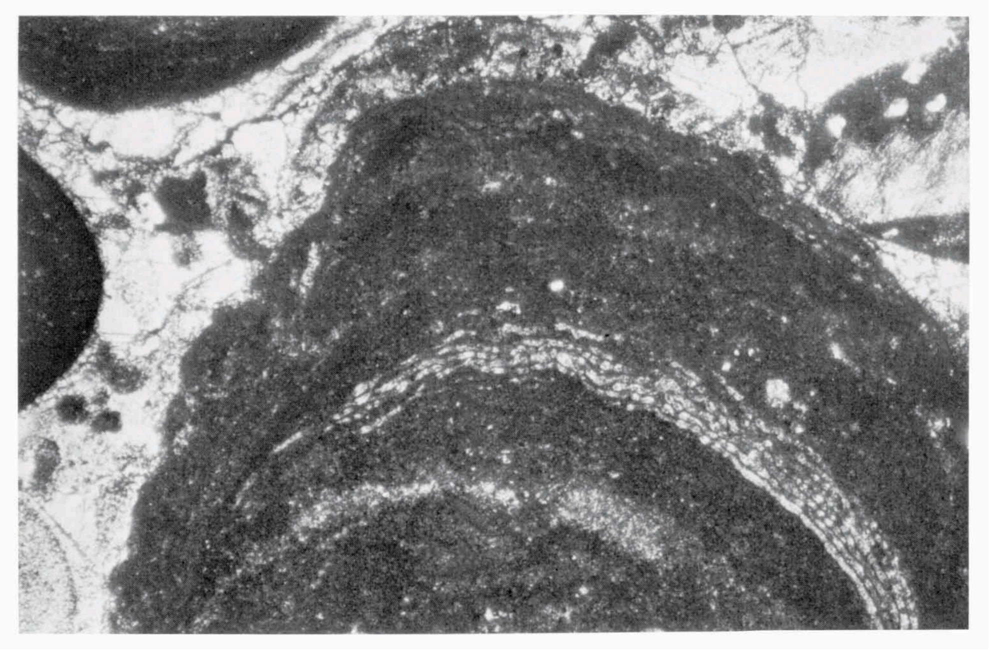


Fig. 4. Thin section of an oncolite from Husryggen 1 (RGM 243 675), showing an alternation of *Girvanella* and *Spongiostroma.*

dant grain type is a neomorphic ooid (f), tiny grains with diameters up to 1.0 mm, composed of several neomorphic sparry calcite crystals, featuring still vaguely the original concentric structure (Fig. 3a and 5b). The coated grains (g) are larger, usually bioclasts coated by an ooidal cortex which is thinner than the radius of the nucleus (Fig. 3b). A variety of the coated grains are the composite ooids (h), with a large nucleus composed of several ooids lumped together (Fig. 3c). Many of the larger concentric ooids have a characteristic lobed outer side of the cortex; these are the (i) lobate ooids (Fig. 3d).

Pisoids — Pisoids (syn.: pisolith) occur widely in certain levels of the Upper Burgsvik Oolite. These grains which have the same structure as the concentric or lobate ooids and the coated grains are larger than ooids, varying from 2.0 to 5.0 mm, some of the coated grains even up to 1 cm. A pisolite is the rock made up of pisoids cemented together.

Oncoids — Oncoids are multiform shaped, (often spheroidal) concentrically laminated grains, sometimes resembling ooids or pisoids, but apparently formed by the accretion of successive layered masses of algal sheats, frequently around a bioclastic nucleus and with bioclasts or quartz grains incorporated in between algal tissues. They vary in size from 1 mm to 5 cm (Fig. 6b). These oncoids are similar to type SS stromatolites (spheroidal structures), concentrically stacked spheroids mode 'C' of Logan et al. (1964). An oncolite is the rock made up of oncoids cemented together. The algal tissues in the oncoids can usually be recognized as such, but their identification is problematic (Fig. 4). The oncolite from the Lower Hamra-Sundre Limestone is known in the literature as '*Sphaerocodium*' limestone.

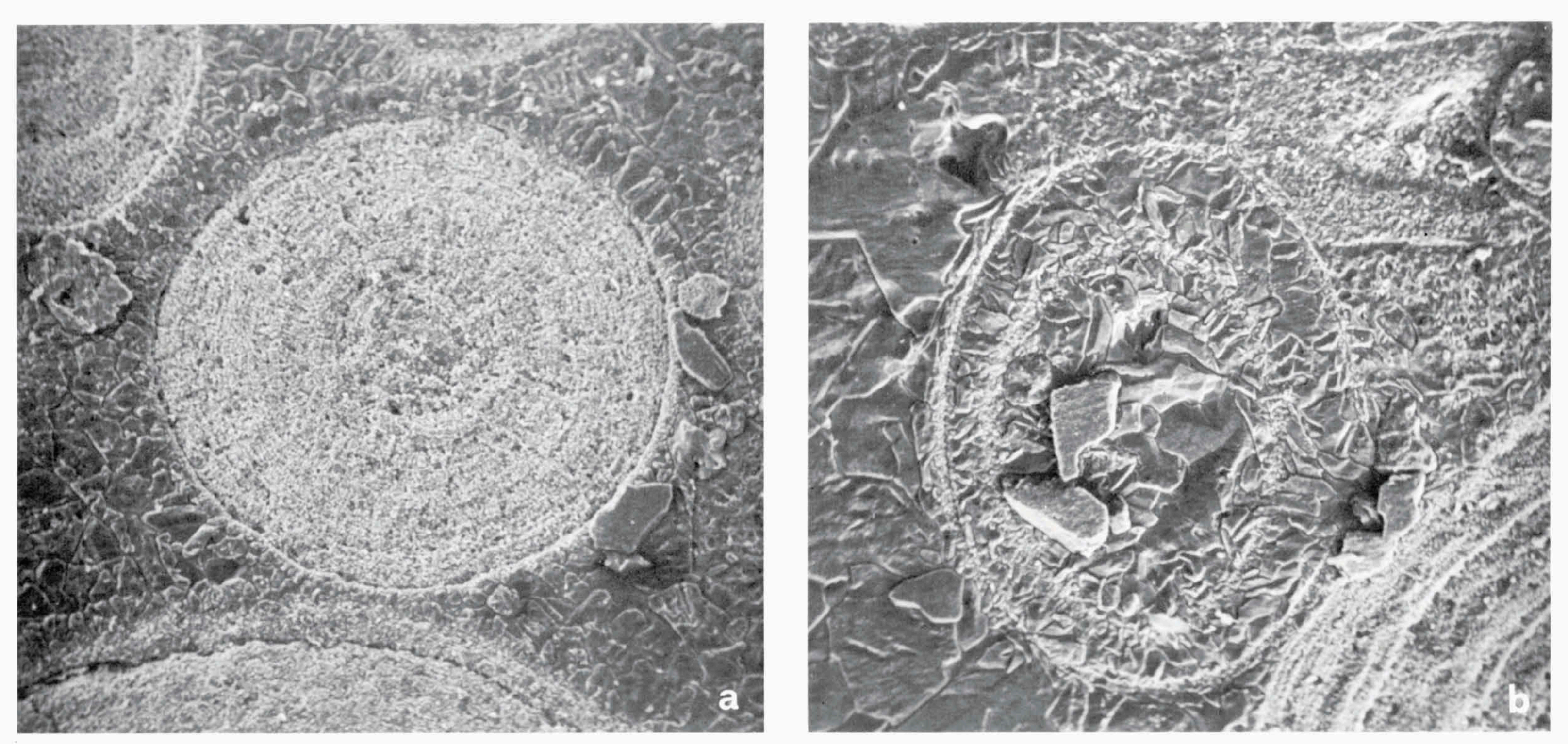


Fig. 5. SEM view of the fine structure of a radial-concentric ooid (130x, RGM 243 676) and a neomorphic ooid (140x RGM 243 677) of facies III at Kulhaken 1.

FACIES

Five facies assemblages were distinguished.
I. Siliciclastic facies: rock types 1 and 2.
II. Bioclastic facies: rock types 3, 4 and 5 (Fig. 6a).
III. Oolitic/pisolitic facies: rock types 6 and 7 (Fig. 6b, Fig. 7a).
IV. Oncolitic/biostromal facies: rock types 8 and 9 (Fig. 7b).
V. Crinoidal facies: rock type 10.

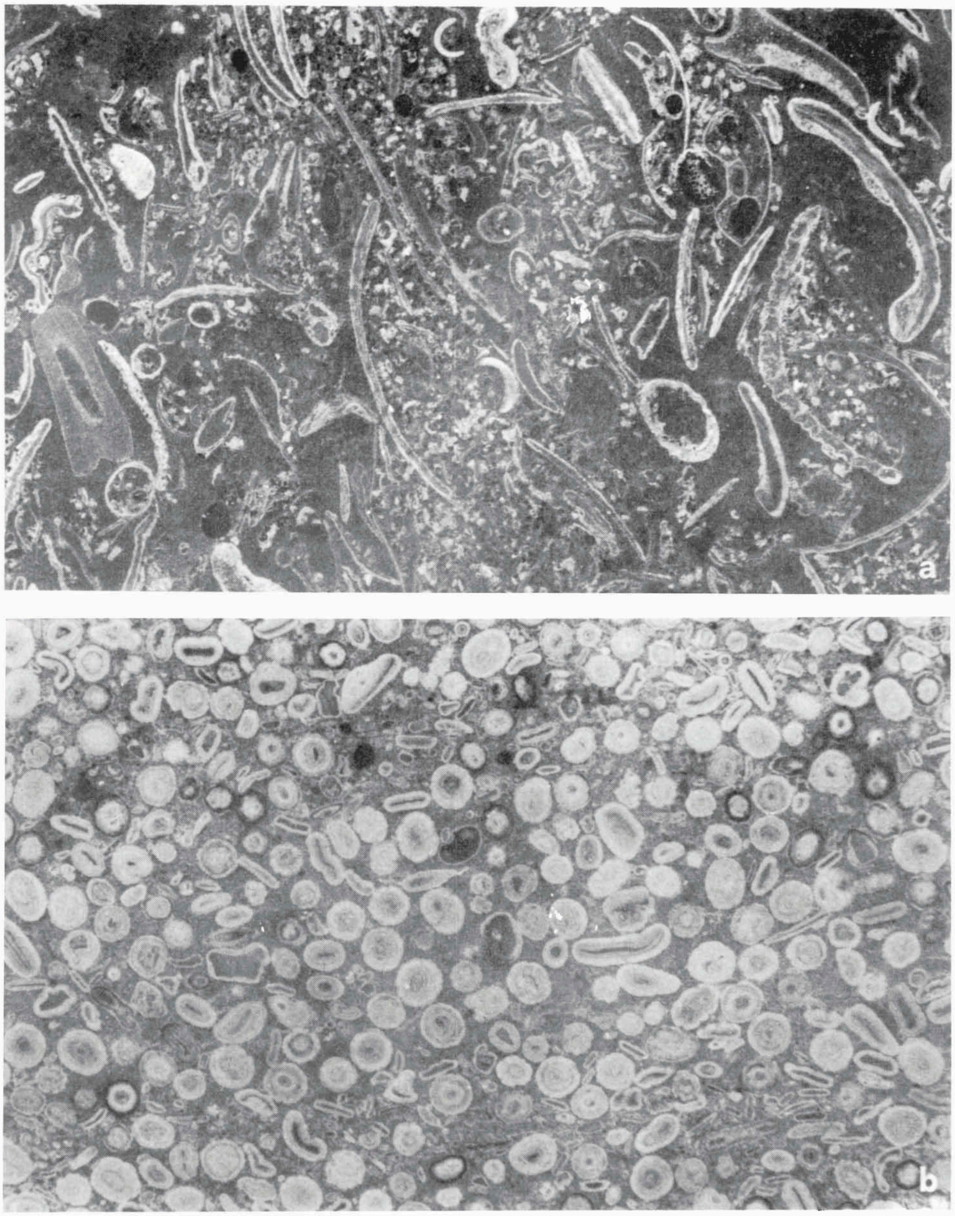


Fig. 6. a. Thin section of the bioclastic grainstone of facies II, Husryggen 2b, RGM 243 678; b. Polished slab of facies III, showing point contacts and horizontal or slightly imbricated pisoids, Kulhaken 1, RGM 243 679.

SECTIONS

In order to study the relation and distribution of the rock types and facies, 18 sections were measured in the interval defined. Some additional observations were made in between section localities. A more or less continuous sequence was observed in the Hoburgen-Husryggen-Kättelviken area, in the southernmost part of the island. One section was measured at Hoburgen 2 (Fig. 9), one at Husryggen 1, six at Husryggen 2, one each at Husryggen 4, at Kättelviken 7 and at Kättelviken 6

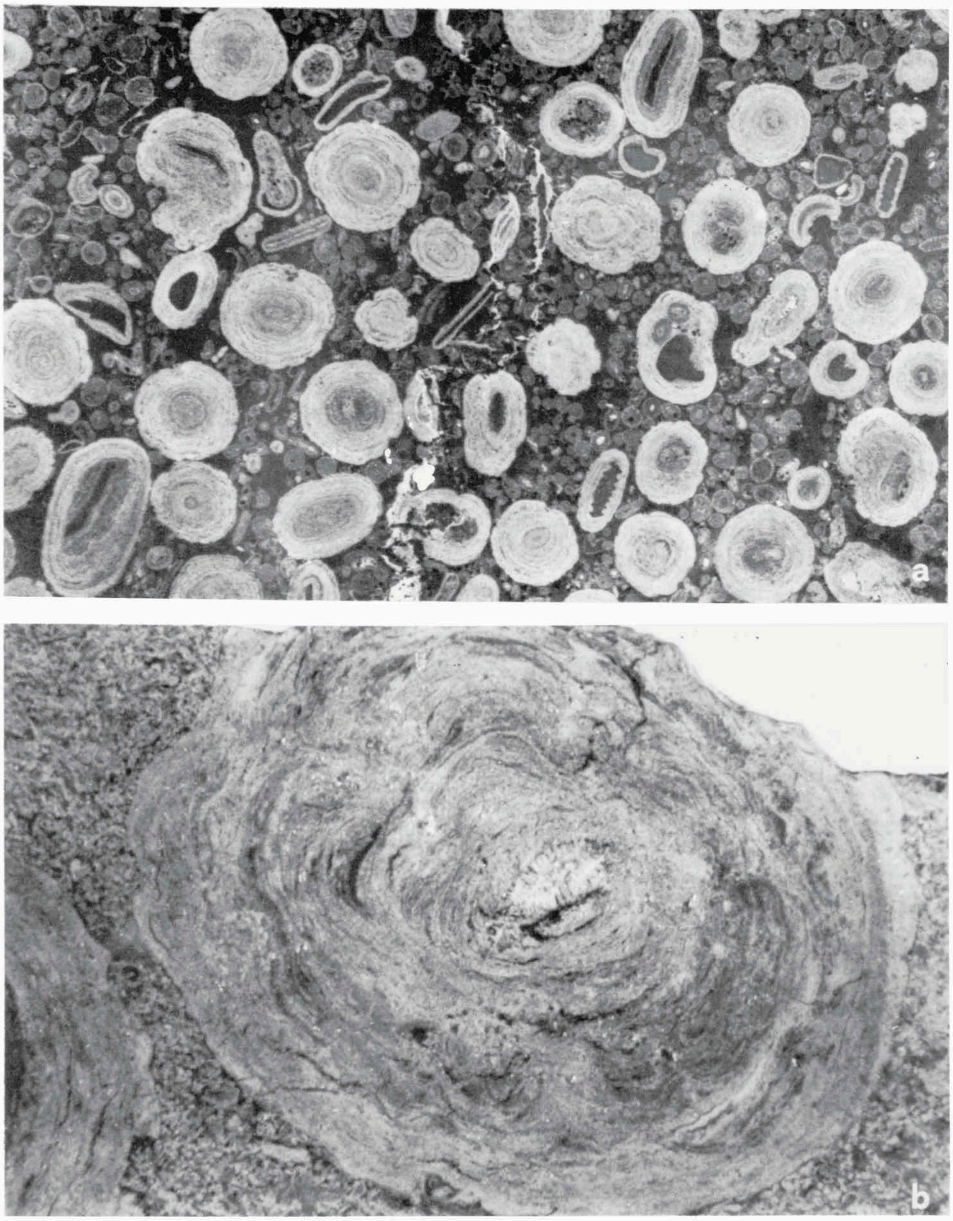
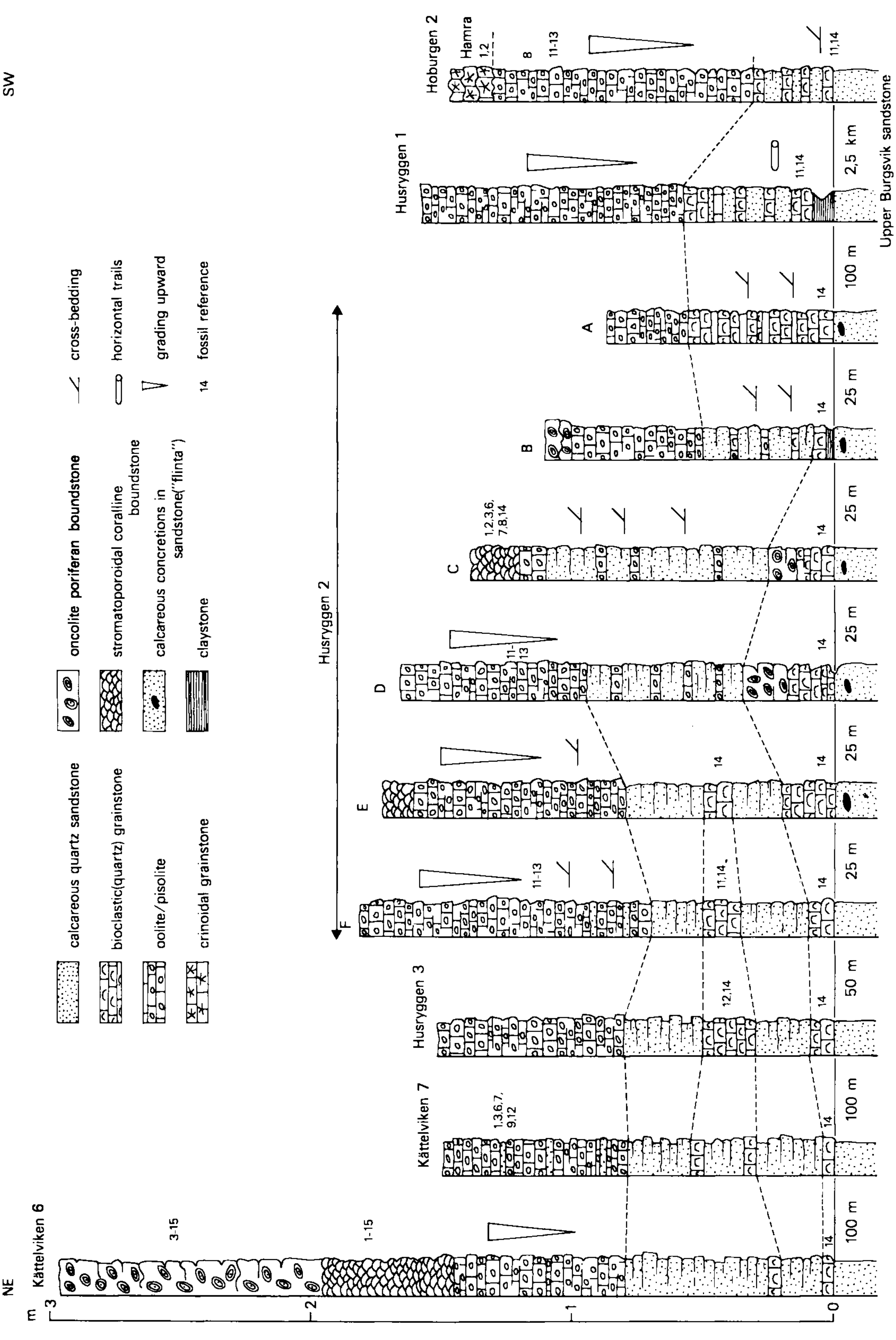


Fig. 7. a. Thin section of facies III, showing the bimodality of the ooids, Valar 2, RGM 243 680; b. Polished slab of facies IV, showing a large oncoid with a nucleus of *Hallopora*, Kättelviken 6, RGM 243 681.


SW
NE
Kättelviken 6
Kättelviken 7
Husryggen 3
Husryggen 2
Husryggen 1
Hoburgen 2
Hamra
A
B
C
D
E
F
Upper Burgsvik sandstone
m
0
1
2
3
100 m
100 m
50 m
25 m
25 m
25 m
25 m
25 m
100 m
2,5 km
3-15
1-15
1,3,6,7,9,12
12,14
11,14
11-13
1,2,3,6,7,8,14
11,14
1,2
8
11-13
14
calcareous quartz sandstone
bioclastic(quartz) grainstone
oolite/pisolite
crinoidal grainstone
oncolite poriferan boundstone
stromatoporoidal coralline boundstone
calcareous concretions in sandstone("flinta")
claystone
cross-bedding
horizontal trails
grading upward
fossil reference

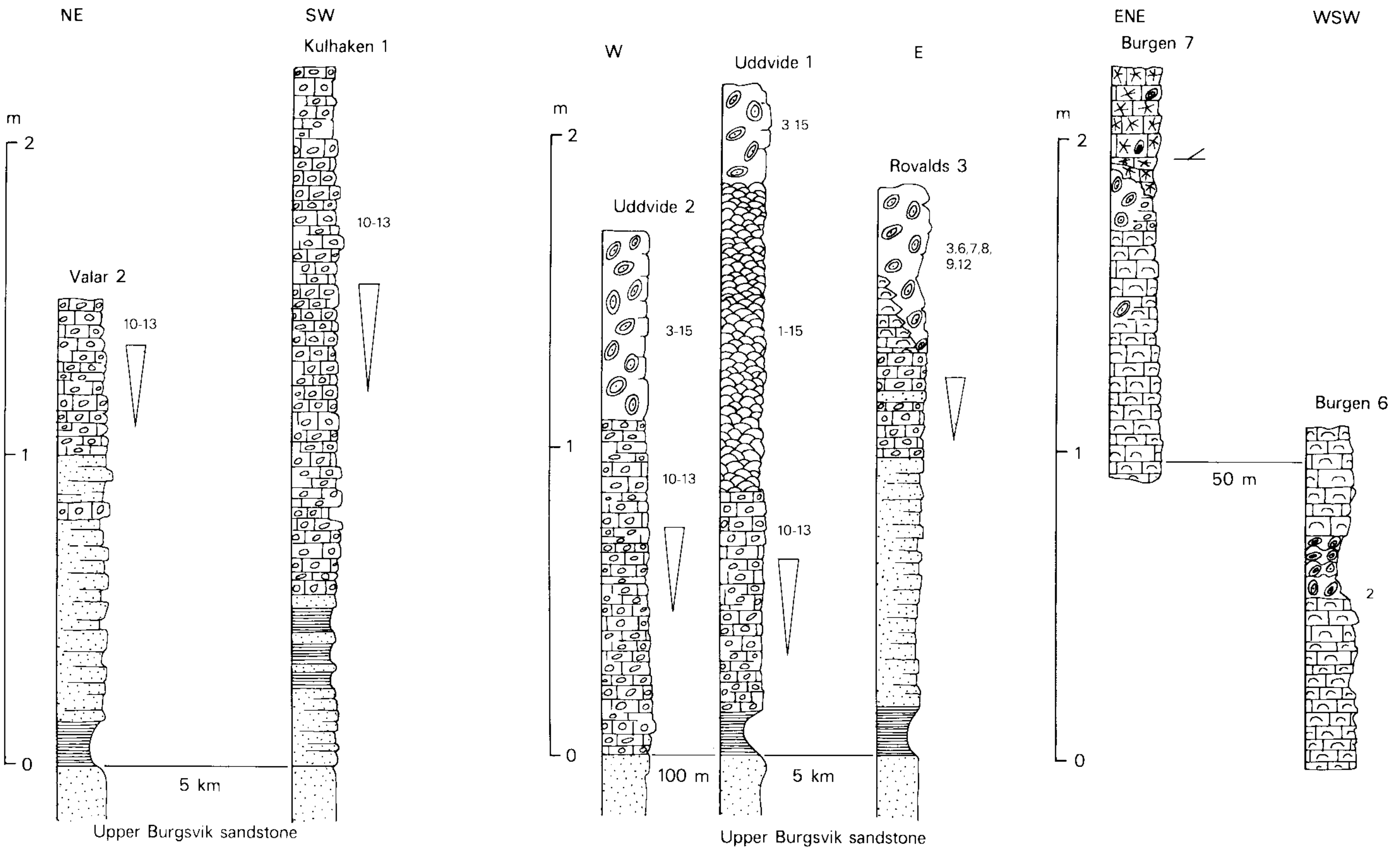


Fig. 8. Correlation of the sections between Hoburgen 2 and Kättelviken 6 (above), and at Kulhaken 1 and Valar 2, Uddvide 1, 2 and Rovald 3, and Burgen 6, 7 (below).
Porifera: 1. *Lophiostroma schmidti,* 2. *Parallelostroma typicum,* 3. *Favosites forbesi,* 4. *Thecia confluens,* 5. *Syringopora schmidti,* 6. *Alveolites* sp., 7. *Phaulactis cyathophylloides;* Bryozoa: 8. *Ptilodictya lanceolata,* 9. *Hallopora* sp.; Brachiopoda: 10. *Isorthis canaliculata,* 11. *Protochonetes striatellus,* 12. *Atrypa reticularis,* 13. *Coelospira pusilla;* Mollusca: 14. *Pteronitella retroflexa,* 15. *Loxonema* sp.

Fig. 9. View of the section at Hoburgen 2, showing sharp contact between facies I and II. Cross-bedding is seen in facies III.

Fig. 10. View of section B at Husryggen 2, showing erosive contact between facies I and II. A sandstone layer rich in *Pteronitella retroflexa* valves is seen just below the hammer's head. Cross-bedding is found in facies III.

(Fig. 7). The interval studied in this area starts almost everywhere with a bioclastic quartz grainstone, generally about 10 cm thick, with crinoids at the base and *Pteronitella* valves (predominantly with their convex side upward) in the upper part. The contact between the Upper Burgsvik Sandstone and this bioclastic grainstone is often erosive (Fig. 10). Locally, a dark grey claystone lense is present of about 10 cm thick and several metres wide. An oncolite ridge is found in Husryggen 2 on top of this basal bioclastic grainstone with a maximum thickness of 35 cm and several tens of metres wide. There is a variable unit ranging from 20 cm to about 1 m in thickness between the bioclastic grainstone or oncolite and the oolite composed of alternating calcareous quartz sandstones and bioclastic grainstones, the latter often being slightly oolitic. The sandstone is usually cross-bedded. The tabular cross-bedded sandstone at Hoburgen 2 (Fig. 9) points towards unidirectional currents mainly from the east. A level with horizontal (biogenic) trails can be found in the sandstone at Husryggen 1. The transition to the overlying oolitic grainstone is usually a sharp one. The oolite is slightly different in colour, yellowish and pink, with a more pronounced weathering than the underlying unit. The oolite mostly shows an indistinct cross-bedding, indicating bi-directional currents. The oolite usually passes into a pisolite. This grading upward is a very common feature in the Upper Burgsvik Oolite. In most sections the oolite/pisolite is the highest unit exposed since it more or less coincides with a Pleistocene raised beach at Husryggen. The oolite/pisolite is succeeded in some sections by an irregular oncolite, locally with small biostromes (in the sense of Nelson et al., 1962). These biostromes, mainly composed of sponges, reach a maximum thickness of about 1 m, being several metres wide. The oncoids from the surrounding oncolite are mainly formed around sponges, bryozoans, crinoids and brachiopods, with some quartz grain admixture. The oncolite, or the poriferan boundstone if present, is erosively succeeded by the crinoidal grainstones and packstones of the Lower Hamra-Sundre Limestone.

Two sections were measured north of the Hoburgen-Husryggen-Kättelviken area: Kulhaken 1 and Valar 2 (Fig. 7). The difference with the area described above is a clay-rich unit on top of the oolite/pisolite bed, with a distinct grading upward, at Kulhaken 1.

Another two sections were measured in the quarries of Uddvide: Uddvide 1 and Uddvide 2 (Fig. 11). The oolite mostly rests directly on the Upper Burgsvik Sandstone. There is a thin claystone lense in between the sandstone and the oolite at Uddvide. The grading upward from oolite into pisolite into oncolite is characteristic in both sections. We found a small poriferan biostrome in the oncolite at Uddvide 1, with a maximum thickness of one metre and several metres wide. One section was measured northeast of Uddvide at Rovalds 3 (Fig. 7). A thin claystone bed is found on top of the Upper Burgsvik Sandstone, succeeded by 80 cm of thinly bedded calcareous quartz sandstone with casts of bivalves and brachiopods. The oolite/pisolite bed is relatively thin, only 35 cm, with thin quartz sandstone beds, followed by the oncolite which laterally passes into a coarse grained bioclastic grainstone.

Two more sections were measured in the northeastern part of the area, one at Burgen 6 and one at Burgen 7 (Fig. 7). The Upper Burgsvik Sandstone is not exposed in these localities. The lowest part of the succession was measured at Burgen 6, where we found a prevailing coarse grained bioclastic, sometimes slightly oncolitic, grainstone to packstone with an intercalated unit of 29 cm oncolite with sponges in life position (Fig. 12) at the base. The remaining part of the succession was found in Burgen 7, although we have not been able to establish a correlation. The coarse grained bioclastic grainstones to packstones become increasingly richer in oncoids, a development that is cut off by the erosive cross-bedded crinoidal grainstone, still containing some oncoids, of the Lower Hamra-Sundre Limestone.

Fig. 11. View of the section at Uddvide 2, showing sharp contact between facies I and facies III.

Fig. 12. View of the section at Burgen 6, showing an intercalated oncolite-unit (29 cm), with stromatoporoids (S) in life position, in a coarse grained bioclastic grainstone to packstone.

INTERPRETATION

Facies I — The granulometric data from the calcareous quartz sandstones show an average median of 0.10 and a sorting of 1.12 (Trask's So). The log-probability curves indicate two sub-populations within each sample. According to Visher (1969) three sub-populations are present in sediments, as the result of three means of transport: 1) rolling, 2) saltation, and 3) suspension.

The coarser sub-population (rolling transport) is absent in our curves, since it is predominantly composed of shell material that dissolves during removal of the calcite cement which is brought about by the treatment of the samples in the laboratory. Consequently two sub-populations remain: the saltation and the suspension population. The saltation population is a steep line (well sorted) composed of two straight segments. This, in combination with the grain size statistics, is very characteristic of beach sediments (Visher, 1969), particularly from the foreshore (Emery, 1960) of a beach, where swash and backswash represent two different transport conditions and presumably produce two separate saltation populations in opposite flow directions. The sedimentary (tabular cross-bedding and parallel lamination) structures are not uncommon in a beach environment. The thin claystone lenses, which in some places occur at the contact with the Upper Burgsvik Sandstone, were possibly formed in shallow depressions on the back shore (Emery, 1960), the only place where fine material could settle. Kukal (1971) listed a few characteristics of beaches formed of fine grained deposits (Md 0.29) compared with beaches with coarse grained deposits.

Fine grained beaches reach a width of several kilometres, with a slight slope. They are found at smaller seas, bays or lagoons, usually in sheltered bays, or in the case of a barrier or bar at the landward or lagoonward side.

Facies II (Fig. 6a) — The predominantly bioclastic grainstones of this facies with quartz grains and/or ooids, are characterized by the occurrence of numerous bivalves, nearly always found with their convex side upwards. Besides bivalves there is a large variety of other — usually broken — bioclasts of trilobites, brachiopods, crinoids, and occasional bryozoans or gastropods. This facies can be considered a transition between the underlying calcareous quartz sandstone (facies I) and the overlying oolite (facies III).

The sediments of the lower foreshore of a beach environment are characterized by shells and various organic debris according to Thompson (1937). Since the preservation of a beach is manifestly contingent on its burial before erosion, the sequence from sandstones to bioclastic grainstones with bivalves might point towards a gradual or occasional submergence of the shore; a tendancy that is continued in the overlying oolite.

Facies III (Fig. 6b, 7a) — The ooids from the Upper Burgsvik Oolite resemble, with their predominant concentrical and symmetrical constitution, mostly those formed in recent agitated environments like in the ooid shoals of the Great Bahama Bank (Bathurst, 1975) or in the ooid tidal deltas of the Persian Gulf (Loreau & Purser, 1973). The ooids from the quiet water environment of the Laguna Madre (Freeman, 1962) show a completely different irregular asymmetrical coating of the nucleus. The ultrastructure of the outerside of the cortex of ooids can give information about their genesis (Loreau, 1973). Under the scanning electronic microscope the Burgsvik ooids unfortunately show only equidimensional nannocrystals, which are not indicative at all. The abundant, though indistinct, cross bedding in the Upper Burgsvik Oolite indicates bi-directional currents, probably of tidal origin. A characteristic feature of the Burgsvik ooids is their relativly large size, with an average between 1 and 2 mm, grading upward in grains of pisoid size (up to 5 mm). This grading upward does not exclude the presence of smaller grains. The pisolite actually consists of grains of pisoid and of ooid size, clearly showing a bimodal grain size distribution. Kukal (1971) pointed out that bimodality may originate by the mixing of several fractions, for instance at the transition of two environments, or by erosion. The occurrence of a bimodal sediment suggests, in the case of a marine sediment, a strait or beach environment of deposition.

Ooids from modern environments are rarely larger than 1 mm. Bathurst (1975) suggested that this upper size limit is possibly due to the equilibrium between the rate of loss of mass by abrasion, and gain by ooidal growth.

The maximum size would be controlled largely according to the level of turbulence. Small ooids are formed in an environment with a high turbulence, e.g. waves or strong tidal currents; large ooids in a moderately turbulent environment, e.g. gentle currents. Another factor influencing the upper size limit of ooids is the time at which they are finally buried (Bathurst, 1975): the faster their accumulation, the quicker the burial and the smaller the grain size. The coarser the ooid, the longer it has been exposed in a growth environment.

Pisoids are known to grow in caliches, like the vadose pisoids described by Dunham (1969). These pisoids interfered with each other's growth and show a downward elongation, indicating that they were stationary. The pisoids from the Upper Burgsvik Oolite show point contacts, while elongate grains have been deposited predominantly horizontal or slightly imbricated, indicating that they have been transported (Fig. 6b). Consequently it seems most likely that the ooids have been deposited in a high turbulent environment, possibly under the influence of wave action, while the pisoids were formed in a moderately turbulent environment, possibly below the zone of wave activity, but still influenced by (tidal) currents. Smaller ooids occasionally infiltrated the pisoid forming environment, giving rise to the bimodal grain size distribution.

Some of the ooids and pisoids have been built up by fibrous algae (Hadding, 1959). Algae probably have influenced the growth of the lobate ooids and pisoids, which then can be considered as embryonic oncoids. Neomorphism of smaller ooids (neomorphic ooids) might be attributed to the inversion from aragonite to calcite. Sandberg (1975) suggested that ancient ooids were originally predominantly or exclusively calcite since they retain a fine texture that would have been altered into neomorphic calcite if they had originally been deposited as aragonite. The differential diagenetic behaviour of coexisting ooids in the Upper Burgsvik Oolite would mean that the neomorphic ooids were originally deposited as aragonite, the remaining — usually larger ones — as calcite. Aragonite or calcite precipitation is controlled by the Mg/Ca ratio of the sea water ($<2/1$: calcite; $>2/1$: aragonite). The abundance of originally calcitic non-skeletal grains in ancient sediments, compared with the predominant formation of aragonitic non-skeletal grains in present day seas (Mg/Ca ratio: 5/1), can be explained by supposing a lower Mg/Ca ratio in ancient seas (Sandberg, 1975). Accordingly, the majority of the ooids and pisoids from the Upper Burgsvik Oolite were deposited under normal marine conditions prevailing at that time (with a low Mg/Ca ratio) originally as calcite. The aragonitic, now neomorphic calcite, ooids were originally formed in an environment with a higher Mg/Ca ratio, e.g. brackish or fresh water, and later mixed with the ordinary marine ooids and pisoids. Such a mixing of elements from different environments is a common feature in beach deposits (Kukal, 1971), which is also indicated by the bimodal grain size distribution.

Facies IV (Fig. 7b) — The growth of oncoids usually takes place in submerged shoal water areas or areas low in the intertidal zone, where the spherical bodies are constantly moved by currents or waves (Logan et al., 1964). Mode 'C' oncoids (concentrical spheroïds) indicate more ore less continual motion, which results in the growth of concentrical lamination. This type is probably restricted to areas continually under water and sufficiently agitated to permit almost continual motion of the oncoid. In the same environment biostromes could develop, thus forming a close association between oncolite and boundstone.

Facies V — Contrary to the rocks of facies II we find here coarse grained grainstones and packstones predominantly composed of crinoid ossicles. Cross-bedding and channel structures indicate deposition by currents, whereas the occasional occurrence of mud (packstones) indicates more quiet conditions. The pelmatozoans probably lived in an open marine and more off-shore environment.

Paleobiology

LIFE ASSEMBLAGES

The burial assemblages in the Upper Burgsvik and Lower Hamra-Sundre Beds of southern Gotland vary. The faunas of facies I and II mainly reflect life assemblages, whereas the assemblage of the oolite (facies III) was transported, as is demonstrated by the brachiopods (Hurst, 1975 a). The flora and fauna of the oncolite (facies IV) is mainly a life assemblage, although transported elements occur. The assemblages consist of representatives of several taxa (Table 1):

Algae — Lindstrom (1888) described *Girvanella* from this region. Rothpletz (1913) named *Sphaerocodium gotlandicum* and *S. munthei* in a monograph on Silurian algae from Gotland. Algae are frequently found as balls in the Eke and Hamra Beds (Rothpletz, 1913). The Hamra oncolite is still known as the '*Sphaerocodium*' limestone (Manten, 1971). Wood (1948) demonstrated that *Sphaerocodium* consists of an intergrowth of three distinct organisms. He named the encrusting organism composed of small dichotomous branching filaments *Rothpletzella,* whereas subcircular or sinuous tubes growing around a substrate were defined as *Wetheredella.* The remaining filamentous structures were labelled *Girvanella.* Wood (1948) interpreted *Wetheredella* structures as foraminiferid, but recently its algal affinities were suggested (e.g. Copper, 1976; Riding, 1977a). Rothpletz (1913) also described structureless oncoids as *Spongiostroma,* but we suspect that these are merely recrystallised *Girvanella* balls (Fig. 4). Other oncoids with a radial structure were identified as *Solenopora.* Hadding (1941) discussed the importance of calcareous algae as rock-formers in the Silurian of Gotland. He considered *Sphaerocodium* as a junior synonym of *Girvanella.* We observed both *Rothpletzella* and *Girvanella* alternating with '*Spongiostroma*' in the Hamra oncoids.

Porifera-Stromatoporoidea — Mori (1970) noticed that in the Eke Beds five species occur, whereas in the Hemse Beds twenty-three are present. Of these five species *Plectostroma scaniense* was only collected in the southwestern exposures of the Eke Beds, which are rich in algae. Apart from some rare finds of *Lophiostroma schmidti* in facies III, no stromatoporoids occur in the predominantly siliciclastic deposits of the Burgsvik Beds. Most species from the Eke Beds are also present in the Hamra-Sundre Beds. *Plectostroma scaniense* and *Lophiostroma schmidti* are frequently observed in the Hamra oncolite, as well as in the uppermost algal Eke Beds. Stromatoporoid coenostea are mostly small and infrequent in the Eke and Hamra Beds. Coenostea grew larger in the Upper Hamra-Sundre Beds. The stromatoporoids are an important constituent of reefs (Manten, 1971). Stromatoporoids from the Hamra oncolite are more often found in the biostromes than in between the oncoids.

Porifera-Tabulata — Favositids and alveolitids are a characteristic element of the Hamra oncolite. A large collection of favositids and alveolitids, most of them in life position, was collected during several field trips at Uddvide 1 and 2. Several 'species' and 'subspecies' could be distinguished in this material applying current taxonomic methods based on e.g. calicle ('corallite') diameters and the occurrence of septal spines: *Favosites forbesi, F. pseudoforbesi pseudoforbesi, F. pseudoforbesi ohesaarensis, F. pseudoforbesi muratsiensis, F. opinabilis,* and *F. similis.* I consider these 'species' as within the range of *F. forbesi* Milne Edwards & Haime (Fig. 13) on account of a paleobiological investigation of favositids from Gotland

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Table 1. List of the fauna collected or described from the Eke, Burgsvik, and Hamra-Sundre Beds. The table is compiled after various sources including: Brood, 1970, 1975; Calef & Hancock, 1974; Hede, 1919, 1960; Hurst, 1975a; Jux, 1957; Martinsson, 1962; Minato, 1961; Mori, 1970; Regnèll, 1956; and Wedekind, 1927.

* Recently the systematic position of the tabulates has become a matter of dispute because of the rediscovery of sponges with a compound skeleton. Kirkpatrick (1911) discovered *Merlia normani,* an incrustive sponge found off the coast of Madeira. Unfortunately *Merlia* was not found elsewhere. Consequently Kirkpatrick's work felt into oblivion until Hartman & Goreau (1966, 1969) found several new other coralline sponges off Jamaica. In 1970 Hartman & Goreau established the class Sclerospongiae for these organisms with a compound skeleton of siliceous spicules, proteinaceous fibres and calcium carbonate. The latter is laid down as a basal mass in which spicules might be trapped. The organization of the living tissue is basically similar to that of the demosponges except that it is divided into units each of which extends down into the upper layer of the basal skeleton. The remainder of the basal skeleton is cutt off from living tissue by tabulae or by a solid calcareous infilling.

Some sclerosponges such as ceratoporellids (Hartman & Goreau, 1972) and the tabulosponges (Hartman & Goreau, 1975: Mori, 1976) show striking similarities with chaetetids and favositids. Although Hartman & Goreau (1975) consider the former related to sclerosponges they reject a sponge interpretation for favositids because of presumed differences in microstructure between favositids and *Acanthochaetetes wellsi.* However, the primary microstructure of favositids was not aragonitic but calcitic. As both in acanthochaetetids and favositids tabulae, septal spines and a similar type of increase are found I think the favositoid skeleton was more probably produced by a sponge than by a coral (see also Flügel, 1976).

Although more evidence is needed in favour of a sponge and/or coral interpretation, I list the tabulates as Porifera because I consider this the least unlikely interpretation for most tabulates.

Species	Eke-Beds	Burgsvik Beds		Hamra-Sundre Beds	
Porifera-Stromatoporoidea					
Plectostroma scaniense Mori, 1970	—			—	—
Stromatopora venukovi Yavorski, 1929	—				
Parallelopora ornata Mori, 1970	—			—	—
Syringostromella borealis (Nicholson, 1891)					—
Parallelostroma typicum (Rosen, 1867)	—			—	—
Lophiostroma schmidti (Nicholson, 1886)	—		—	—	—
Clavidictyon? sokolovi (Riabinin, 1953)				—	—
Porifera-Tabulata*					
Paleofavosites finitimus Klaamann, 1962				—	
Favosites forbesi M. Edwards & Haime, 1851				—	
Thecia confluens (Eichwald, 1854)				—	
Alveolites suborbicularis Lamarck, 1801				—	
Alveolites spp.				—	
Thamnopora spp.				—	
Aulopora spp.				—	
Syringopora schmidti Tchernychev, 1937				—	
Porifera?-Heliolitidea					
Heliolites interstinctus (Linnaeus, 1767)				—	
Propora tubulata (Lonsdale, 1839)				—	
Coelenterata-Rugosa					
Phaulactis cyathophylloides Ryder, 1926				—	
Ectoprocta					
Ptilodictya lanceolata (Goldfuss, 1826)	—			—	
Saffordotaxis ludlowensis Brood, 1970			—	—	
Corynotrypa lauensis Brood, 1975	—			—	
Flabellotrypa sp.				—	
Hallopora sp.				—	
Sagenella sp.				—	
Brachiopoda					
Hesperorthis gotlandica (Schuchert & Cooper, 1932)	—				
Ptychopleurella bouchardi (Davidson, 1847)	—				—
Salopina tubulata (Lindström, 1861)	—				
Isorthis canaliculata (Lindström, 1861)	—		—	—	—
Resserella canalis (J. de C. Sowerby, 1839)	—				
Dalejina hybrida (J. de C. Sowerby, 1839)	—				
Linoporella punctata (de Verneuil, 1848)				—	
Dictyonella capewellii (Davidson, 1848)	—				
Leptaena spp.	—		- - -	—	—
Lepidoleptaena sp.			—	—	—
Brachyprion sp.	—		—	—	—
Shaleria aff. *ornatella* (Davidson, 1871)	—	- - -	—		
Strophonella euglypha (Dalman, 1828)	—				
Coolinia pecten (Linnaeus, 1758)	—				

Species	Eke-Beds	Burgsvik Beds		Hamra-Sundre Beds	
Brachiopoda					
Protochonetes striatellus (Dalman, 1828)	—	—	—	—	—
Anastrophia deflexa (J. de C. Sowerby, 1839)	—				—
Rhynchotreta cuneata (Dalman, 1828)	—				
Microsphaeridiorhynchus nucula (J.de C.Sowerby,1839)	—	—	—	—	—
Sphaerirhynchia wilsoni (J. Sowerby, 1816)			—	—	
Atrypa reticularis (Linnaeus, 1758)	—	—	—	—	—
Desquamatia sp.	—				—
Spinatrypa sp.				—	
Spirigerina quinquecostata (Munthe, 1910)			—	—	— - - -
Glassia obovata (J. de C. Sowerby, 1839)	—				
Dayia navicula (J. de C. Sowerby, 1839)	—	—	—		
Coelospira pusilla (Hisinger, 1837)	—	—	—	—	—
Homoeospira baylei (Davidson, 1848)	—		—	—	—
Whitfieldella sp.					—
Nucleospira pisum (J. de C. Sowerby, 1839)	—				
Janius barrandi (de Verneuil, 1848)	—				
Striispirifer striolatus (Lindström, 1861)	—		—	—	— - - -
Howellella elegans (Muir-Wood, 1925)	—		—	—	—
Boucotinskia sulcata (Hisinger, 1831)	—		—	—	—
Lingula sp.		—	—		
Mollusca					
Pteronitella retroflexa (Wahlenberg, 1821)		—	—	—	
Pterinea sp.			—		
Nuculoidea pinquis burgsvikensis (Soot-Ryen, 1964)		—	—		
Loxonema sp.				—	
Ascoceras sp.				—	—
Platyceras sp.			—		
Arthropoda-Trilobita					
Proetus signatus Lindström, 1885	—		—	—	
Calymene spp.	—	—	—	—	—
Homalonotus knighti König, 1825			—	—	
Proetus spp.		—	- - -	- - -	- - -
Arthropoda-Ostracoda					
Neobeyrichia ctenophora Martinsson, 1962	—		—	—	—
Neobeyrichia scissa Martinsson, 1962	—				
Neobeyrichia lauensis (Kiesow, 1888)	—				
Beyrichia globifera Martinsson, 1962	—				
Sleia equestris Martinsson, 1962	—			—	—
Hoburgiella tenerrima Martinsson, 1962	—		—	—	—
Aitilia calcarulata Martinsson, 1962	—				
Hamulinavis pirulifera Martinsson, 1962	—				
Clintiella cf. *hyrsiniana* Martinsson, 1962	—				

Species	Eke-Beds	Burgsvik Beds		Hamra-Sundre Beds	
Arthropoda-Ostracoda					
Retisacculus commatatus Martinsson, 1962	—				
Lauella uncinata Martinsson, 1962	—				
Gannibeyrichia biplicata Martinsson, 1962	—				
Kolmodinia cf. *grandis* Martinsson, 1962	—				
Hemsiella anterovelata Martinsson, 1962	—			—	
Calcaribeyrichia bicalcarata Martinsson, 1962	—			—	
Hemsiella loensis Martinsson, 1962	—			—	—
Plicibeyrichia ornatissima Martinsson, 1962	—			—	—
Cryptolopholobus semilaqueatus Martinsson, 1962			—	—	—
Retisacculus semicolonatus Martinsson, 1962				—	
Navibeyrichia balticivaga Martinsson, 1962				—	
Beyrichia barbulimentata Martinsson, 1962				—	—
Lophoctenella angustilaqueata Martinsson, 1962					—
Retisacculus cf. *commutatus* Martinsson, 1962					—
Juviella juvensis Martinsson, 1962					—
Neobeyrichia regnans Martinsson, 1962					—
Echinodermata					
Crinoids					
Palaeasterina antiqua (Hisinger)			—		
Trace fossils					
Chaetosalpinx huismani Stel, 1976				—	
Other trace fossils		- - - - —	—		

which will be published later. This favositid is characterised in all ontogenetic stages by a pattern consisting of large calicles surrounded by smaller ones (Fig. 13). Sokolov (1952, 1962) and Oliver (1975) grouped similar fossils in the genus *Oculipora*. The shape of *Favosites forbesi* coenostea is variable, due to environmental circumstances. Coenostea from in between the oncoids, for instance, are hemispherical or oblate ellipsoidal, whereas coenostea from the sponge biostromes tend to be platy. Probably, branching coenostea were present also. Specimens showing branche-bound features such as peripheral thickening of the calicle wall, compressed calicle shape, etc. are *Thamnopora*-like or *Pachypora*-like. The hard substrate trace fossil *Chaetosalpinx huismani* is seen in one specimen of *F. forbesi*. Stel (1976) considered the relationship between *Ch. huismani* and its host as a parasitic symbiosis. The typical *Thecia swinderениana* (Goldfuss), frequently mentioned from the Hamra Beds, was not observed in our material. Incrustive coenostea of *Thecia confluens* (Eichwald), however, which is probably an ecotype of *Th. swindereniana*, were regularly found. Alveolitids are abundant in the Hamra oncolite. *Alveolites suborbicularis* Lamarck (Fig. 14) is most abundant, and other encrustive alveolitids occur as well. Thamnoporoids are present, but their number and abundance is negligible. Auloporoids abundantly encrust stromatoporoids, tabulates, brachiopods, molluscs, etc. *Syringopora schmidti* Tchernychev is rarely found, whereas syringoporoid fragments are more common. Heliolitids are abundant in several units (e.g. Hemse Beds) of the Silurian of Gotland, but they were not found in the siliciclastic deposits of the Burgsvik Beds. Only *Heliolites interstinctus* (L.) and *Propora tubulata* (Lonsdale) rarely occur in the Hamra oncolite.

Coelenterata-Rugosa — Colonial rugose corals were not found in the Upper Burgsvik and Lower Hamra-Sundre Beds, but they are known from the Upper

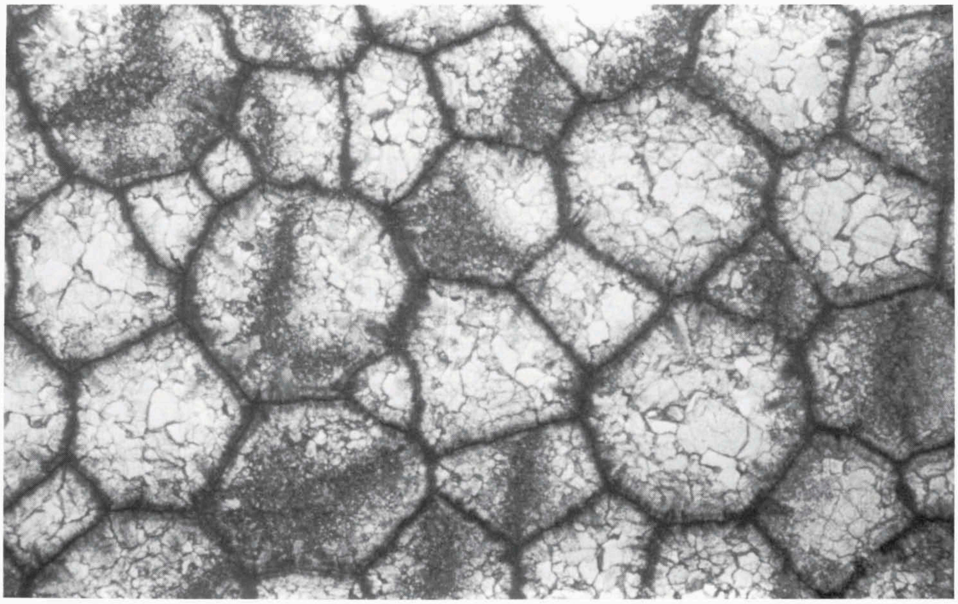

Fig. 13. Transverse section of *Favosites forbesi* Milne-Edwards & Haime, 1851 from Uddvide 2 (× 14; RGM 243 682).

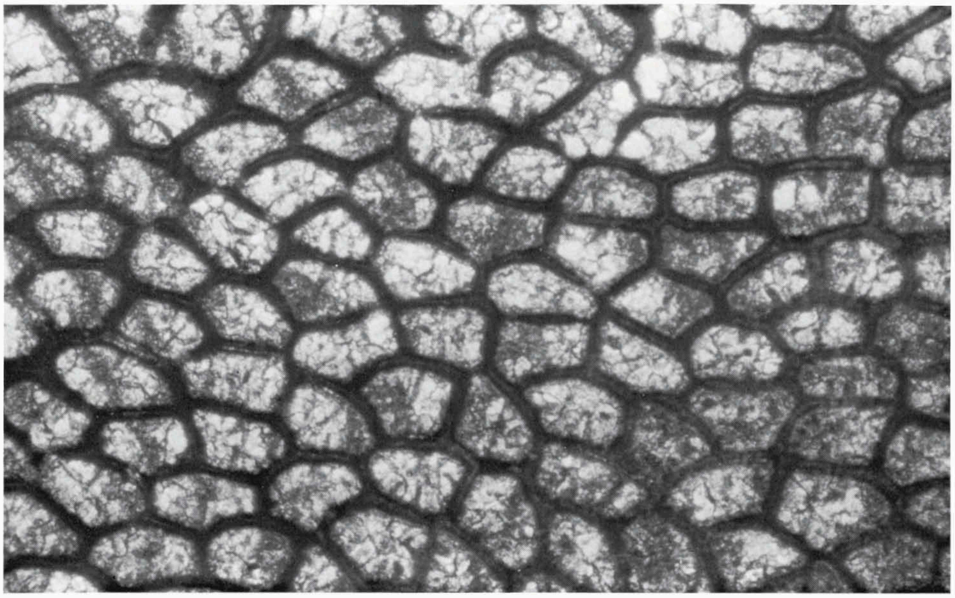

Fig. 14. Transverse section of *Alveolites suborbicularis* Lamarck, 1801 from Uddvide 2 (× 16; RGM 243 683).

Hamra-Sundre reef limestone. *Phaulactis* spp., e.g. *Ph. cyathophylloides,* are numerous in the Hamra oncolite, although negligible in volume.

Ectoprocta — Small colonies of *Hallopora* are frequently found in the Hamra oncolite together with well preserved specimens of *Ptilodictya lanceolata.* Encrusting saganellids occur regularly on sponges, corals and brachiopods.

Brachiopoda — Although several biofacies are distinguished in the Hemse Beds on account of brachiopod faunas, Hurst (1975a) could not find significant faunal differences in the Eke Beds. The regular occurrence of rhynchonellids *(Microsphaeridorhynchus nucula, Rhynchotetra cuneata, Sphaerirhynchia wilsoni)* which are adapted for life in turbulent environments, and the presence of strophomenids *(Strophonella euglypha, Leptaena* spp.), which probably were not able to live under agitated conditions, indicate alternating low and high energy environments during the deposition of the Eke Beds. Few brachiopods occur in facies I: only small specimens of *Protochonetes striatellus, Coelospira pusilla* and *Atrypa reticularis.* Böger (1968) found that *Protochonetes striatellus* specimens from the Upper Eke, Burgsvik and Lower Hamra-Sundre Beds are smaller than specimens of this species from the Lower Hemse Beds, due to environmental restrictions. Atrypids are flattened in these deposits because of turbulence (Copper, 1967). Hurst (1975a) described *Lingula* sp. from the Burgsvik sandstone. This brachiopod was able to live in the fine-grained sands, because of its burrowing ability (see: Thayer & Steele-Petrovic, 1975). *Lingula* also lived in abandoned burrows in *Heliolites interstinctus* colonies from the Hemse Beds (Richards & Dyson-Cobb, 1976). When the burrows were abandoned by the endobiont, *Lingula* settled and could even keep the burrows open in spite of the growth of its host. Consequently Richards & Dyson-Cobb interpreted this relationship as commensalism. However, it is unlikely that the small lingulids (juveniles?) found now within these traces, were able to keep them open. Preferential settlement of *Lingula* larves in the so-called constructive burrow-type of Richards & Dyson-Cobb is also questionable because of the small sample used for the Chi-square test. Therefore the occurrence of *Lingula* within these traces does not suggest that the former settled in a living heliolitid. Moreover this type of trace is more likely made by an embedded hard substrate trace fossil (Stel, 1976). Consequently, we think that a swarm of *Lingula* larves settled by chance in abandoned sediment-filled traces in dead heliolitids. The number of species and individuals increases in facies II. The diverse brachiopod fauna of facies III, indicating an off-shore environment (Hurst, 1975a), is probably transported. Rhynchonellids and strophomenids are present in the Hamra-oncolite, a situation comparable to the one in the Eke Beds. The number of brachiopods was less diverse in the Hamra-Sundre Beds than in deposits older than the Burgsvik Beds (Basset & Cocks, 1974).

Mollusca — The lowermost part of the facies II is characterized by the occurrence of fragments of crinoids, trilobites and accumulations of the bivalve *Pteronitella retroflexa.* The separate, more or less parallel valves are mostly found with their convex side upward. Several valves are accumulated tile-wise (Fig. 10). *Pteronitella* valves were mostly encrusted by alveolitids, auloporids and bryozoans in the Hamra oncolite. Cephalopods are rarely observed in facies II. The gastropod *Loxonema* sp. sometimes occurs within the nuclei of oncoids.

Arthropoda-Trilobita — Few trilobite species occur in the Upper Burgsvik and Lower Hamra-Sundre Beds. We collected a pygidium of *Calymene* sp. at Kättelviken. Trilobite fragments occur frequently in thin sections from facies II and occasionally in facies III and IV.

Arthropoda-Ostracoda — Martinsson (1962, 1967) showed that the beyrichiid fauna of the Eke Beds is faunistically less differentiated than the one of the Hemse Beds. *Sleia equestris, Hemsiella loensis, Neobeyrichia ctenophora, N. scissa* and *N. lauensis* occur in the Eke Beds, containing *Rothpletzella gotlandicum.* Apart from facies II no beyrichiids have been found in the Burgsvik Beds. Some species, already present in the Eke Beds, returned in the Hamra oncolite and several other species appear.

Echinodermata-Crinoidea — Crinoid stem fragments are frequently found in facies II. Equidimensional small stem fragments, like those of facies II, occur in the Hamra oncolite. Their maximum diameter is about 5 mm. Several ossicles are still bound together having a length of up to 20 mm. Manten (1971) supposed that the stem fragment diameter decreases with increased distance from the reef area due to mechanical sorting (see also Ruhrmann, 1971). A maximum stem diameter is found in the crinoidal limestone around the Hoburgen reefs in the Hamra-Sundre Beds. It is not clear wether crinoids producing large stems were limited to distinct localities in separate strata, or that selection caused the differences observed.

Echinodermata-Stelleroidea — Resting traces of *Palaeasterina antiqua* are known from facies I at Hoburgen (Jux, 1957).

Echinodermata-Echinoidea — Echinoids are extremely rare in the Silurian of Gotland. Regnéll (1956) demonstrated that echinoids prevailed in the reef environment. The oncolitic facies of the Eke and Hamra-Sundre Beds was, just as the one of the Tofta Beds, unfavourable to echinoids. They are not known from the Burgsvik Beds either.

Some chitinozoan species are occasionally found in the Eke, Burgsvik and Lower Hamra-Sundre Beds (Laufeld, 1974c). Chitinozoans that occur in the Hamra Sundre Beds are not known from the Eke Beds, whereas several species from the Hemse Beds are present in the Hamra-Sundre Beds.

Fish scales were seen at Uddvide 2 by Dr G. J. Boekschoten (pers. comm.) in the oncolite. Fish scales, probably derived from actinopterygids, are known from the Burgsvik Beds (Spjeldnaes, 1950).

Trace fossils and bioturbation were observed in facies I.

ALGAL ENVIRONMENT

A rich algal flora developed in the Upper Eke and Lower Hamra-Sundre Beds. Lauritzen & Worsley (1974) suggested that the occurrence of algae *(Girvanella)* in the Lower Silurian of the Oslo area might be a reliable depth indicator. Riding

(1975), however, demonstrated vague depth limits for blue-green algae. On the other hand, the SS-C structure of the oncoids (Logan et. al., 1964) indicates that the Eke and Hamra oncolite were formed by algae under agitated conditions. Riding (1977a) described a Recent *Girvanella* from fresh water pools on Aldabra Atoll in the Indian Ocean. Fresh or brackish water pools might have been present during the deposition of Upper Burgsvik and Lower Hamra-Sundre Beds. Consequently, part of the algae found in these beds could have grown in these environments. Gray et al. (1974) described trilete spores and spore tetrads from the Upper Burgsvik Beds. The spores were argued to stem from land vascular plants, although this could not be demonstrated from their morphology and the environment in which they occur. Gray et al. (1974) also demonstrated that the spores were abundant in silty and clayey sediments, whereas they have not been found in coarse grained sediments.

Recently Gray & Boucot (1977) discussed the importance of trilete spores and spore tetrads for land plant evolution. In this paper Gray & Boucot reject the hypothetical possibility that the spores were produced by algae as well. At Gotland, however, the spores are only abundantly found in facies I and II, which we interprete as a beach and lower fore-shore environment. In these environments fresh and brackish water pools might have been present as is indicated by the aragonitic — now neomorphic calcite — ooids and by *Girvanella.* As recent fresh water green algae have resistant spores this could indicate that the trilete spores and spore tetrads might be derived from algae. Moreover, marine algae were abundant in the contiguous deeper environments (facies IV).

TROPHIC ANALYSIS OF THE FAUNA

Terms employed in this trophic analysis are adapted from Imbrie & Newell (1964), Walker (1972), Calef & Hancock (1974), Copper (1974), Hurst (1975b), and Stanton and Dodd (1976). Suspension feeders include low level (0-2 cm), intermediate level (2-20 cm) and high level (> 20 cm) filterers. The term 'collectors' refers to benthic organisms that select food particles from the sediment. Carnivores are passive (corals) or active epifaunal benthic or nectic animal eaters. Swallowers are infaunal deposit feeders that extract nutrients from ingested sediment.

Eke Beds

Suspension feeders — Sessile epifaunal brachiopods like *Microsphaeridorhynchus nucula, Howellella elegans, Homeospira baylei,* and *Atrypa reticularis* are the most important low-level filterers in the biohermal facies. The algal facies is predominated by *Atrypa reticularis* and the vagile low-level suspension feeder *Strophonella euglypha.* The abundance of *M. nucula* in the Eke Beds indicates a shallow agitated environment like that of the *Salopina* community of Calef & Hancock (1974). Yet, the frequent occurrence of strophomenids in the algal facies indicates an alternation of high and low energetic environments. Sponges and ectoprocts are the dominating intermediate level suspension feeders. Crinoids are high level filterers, but there is no evidence that they actually lived in this region.

Collectors — Epifaunal deposit feeders like *Sleia equestris* and other ostracods occur together with some trilobites (scavengers). Collectors are probably not abundant in the algal Eke Beds.

Carnivores — Solitary rugose corals are passive carnivores in the Eke Beds. Active carnivores have not been reported from the unit. Cephalopods are known from the underlying Hemse Beds (Laufeld, 1974b).

Swallowers — Infaunal deposit feeders are not known from the Eke Beds.

The majority of the elements of the flora and fauna in the Eke Beds are algae and suspension feeders. The species composition of the epifaunal low level filter feeders suggests conditions like those of the near-shore *Salopina* community. although an alternation of high and low energetic conditions occurred.

Burgsvik Beds

Suspension feeders — Suspension feeders are less diverse in the Burgsvik Beds, due to an increased substrate mobility. Infaunal filterers (*Lingula* sp.) and low level epifaunal suspension feeders (*Protochonetes striatellus, Atrypa reticularis)* occur in facies I. Intermediate level and high level filterers have not been found. An alternation of high and low energetic conditions developed in facies II, where the same brachiopods occur as in facies I. *Pteronitella retroflexa,* an intermediate level filterer, is abundant in this facies. Sponges and ectoprocts are absent. High level filter feeders probably did not live in this environment, although crinoid ossicles are abundant in some strata. A transported fauna of sessile and vagile brachiopods occurs in facies III, indicating an off-shore environment. The life assemblages of facies III, on the other hand, like the lithology, indicates a near-shore environment. The composition of the brachiopod fauna in the Burgsvik Beds is similar to the *Lingula*/bivalve community of Calef & Hancock (1974).

Collectors — Benthic organisms which select food particles from the sediment are not observed in facies I. Epifaunal deposit feeders *(Sleia equestris)* occur in marly intercalations in facies II. The diversity of the ostracod fauna is low (Martinsson, 1967). Trilobite fragments are abundantly accumulated in facies II, but this does not imply a comparable abundance of scavengers. Grazers and browsers (*Pleurotomaria* sp., *Loxonema* sp.) are sometimes found in facies II and III. Accumulations of actinopterygid scales are known from facies II. Fishes probably lived in this turbulent environment.

Carnivores — Resting traces of starfishes occur in facies I.

Swallowers — Horizontal feeding (?) tracks sometimes occur in facies I and II. *Nuculeoidea pinguis* was an important infaunal deposit feeder in facies II.

Suspension feeders are the dominating trophic group in the Burgsvik Beds. The diversity in this group is low, because of an increased substrate mobility. Consequently, sessile colonial intermediate level filterers (sponges and ectoprocts) could not settle in this environment. The species composition of the epifaunal low level filter feeders indicates a near-shore environment like that of the *Lingula*/ bivalve community. This community occupied the shallowest environment in the successive sequence of depth related communities which Calef & Hancock (1974) proposed for Wenlock/Ludlow siliciclastics of the Welsh Borderland. An increase of depth is demonstrated in facies II and III.

Hamra-Sundre Beds

Suspension feeders — A brachiopod fauna of low level suspension feeders similar to the one of the algal Eke Beds is found in facies IV. Consequently, this fauna indicates that the near-shore agitated conditions of the *Salopina* community returned. The brachiopod fauna becomes more diverse in the Middle and Upper Hamra-Sundre Beds, because of the development of off-shore conditions. This is demonstrated by the increase of vagile epifaunal brachiopods and the transported off-shore fauna in the underlying Burgsvik oolite. Sponges and ectoprocts are the most important intermediate level suspension feeders in facies IV. Tabulates and ectoprocts dominate within the oncolite, whereas stromatoporoids are more abundant in the biostromes. Circumrotary growth forms (Kisseling, 1973; Gill & Coates, 1977) of *Favosites forbesi* coenostea indicate that the colonies, similar to the oncoids, rolled over the sea floor until they were stabilized. This rolling was probably caused by current and not by wave action, because a majority of the colonies is found in life position, suggesting storms did not or hardly influence the benthic community. The orientation of colonies from Uddvide 1 and 2 shows a preferential growth direction, which is interpreted as a growth of the colonies against the prevailing current direction. Crinoids probably are the high level suspension feeders in facies IV and V. The intermediate and high level suspension feeders become more abundant and diverse in the Middle and Upper Hamra-Sundre Beds.

Collectors — Epifaunal deposit feeders are more common and diverse in facies IV than in facies II. Some constituents of the algal Eke Beds occur again. Scavengers (trilobites), grazing and browsing animals (gastropods, fishes) are occasionally found. Collectors were probably not abundant.

Carnivores — Passive carnivores *(Phaulactis cyathophylloides)* are regularly found.

Swallowers — Infaunal deposit feeders are not observed in facies IV or V.

The most important elements of the flora and fauna in the Hamra-Sundre Beds consist of algae and suspension feeders. The diversity of the suspension feeders increased because of a diminishing substrate mobility. The species composition of the low level epifaunal suspension feeders indicates an environment similar to the one of the near-shore *Salopina* community. This community occupies a deeper environment than the *Lingula*/bivalve community in the Burgsvik Beds. As a result of this, a change of the sea level must have occurred, giving rise to the development of off-shore communities in the Middle and Upper Hamra-Sundre Beds.

The entire succession indicates a shallowing up (regression) in the Eke and Burgsvik Beds, followed by a deepening (transgression) in the Upper Burgsvik and Hamra-Sundre Beds. The transgressive phase started with facies II.

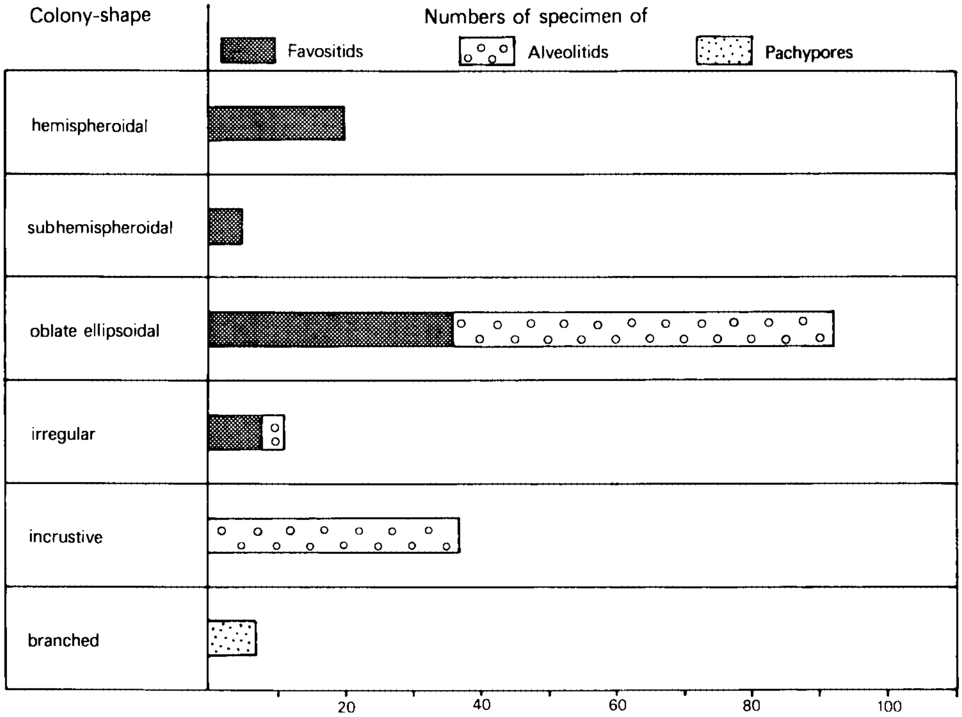

Fig. 15. Histogram of the colony shapes of various tabulates from the Hamra-oncolite.

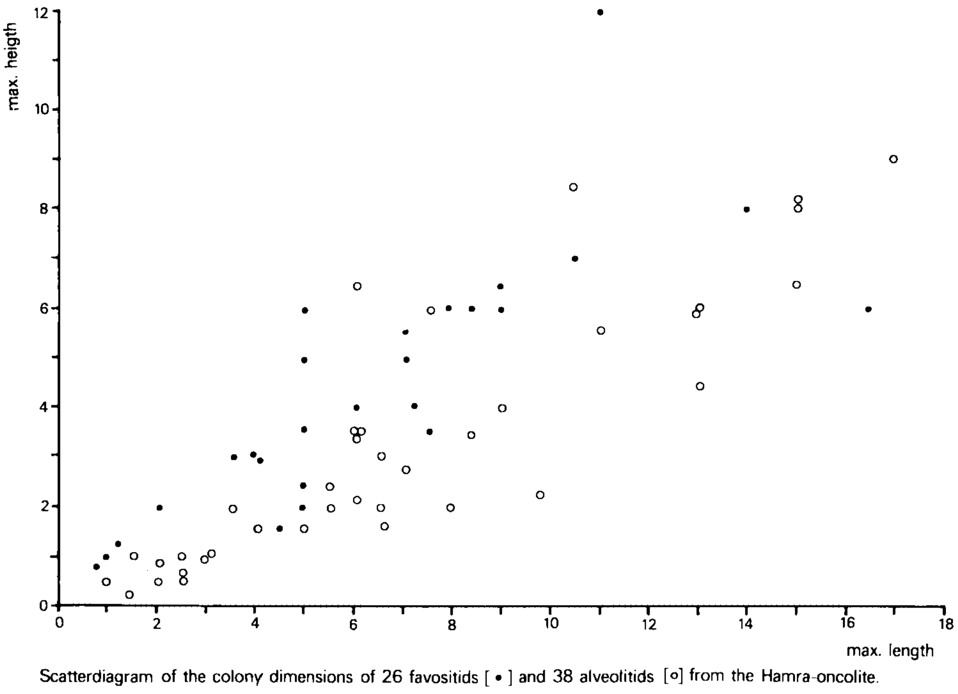

Fig. 16. Scatterdiagram of the colony dimensions of 26 favositids (.) and 38 alveolitids (o) from the Hamra-oncolite at Uddvide 1, 2.

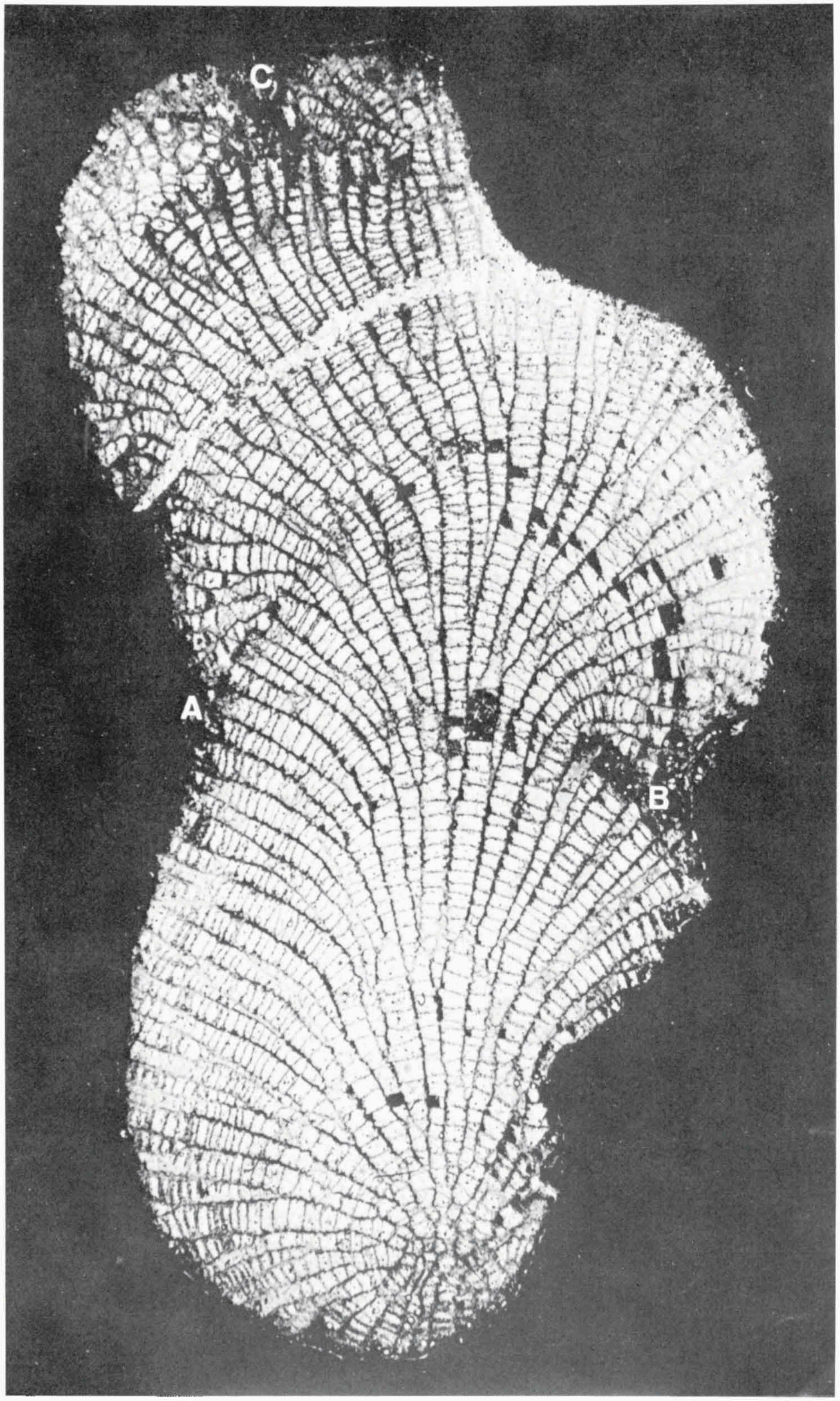

Fig. 17. Acetate peel of a *Favosites forbesi* colony from Uddvide 2 (RGM 243 684), showing interaction of algae, × 3. For explanation see page 33.

INTERACTION OF ALGAE AND TABULATES

The occurrence of stromatolitic laminae within colonial organisms is known from recent and fossil animals. Ladd (1950) and van den Hoek (1969) described the competition between corals, together with their overwhelming of crustose coralline algae from the Caribean Sea. Hadding (1959) demonstrated intergrowth of algae with stromatoporoids, tabulates and bryozoans. He considered this intergrowth as a symbiosis, although no direct evidence was given. Mori (1970) described the occurrence of stromatoporoids associated with calcareous algae from the Eke and Hamra-Sundre Beds. Sutherland (1975) discussed the competition between colonial and solitary rugose corals and algae in the Upper Carboniferous of

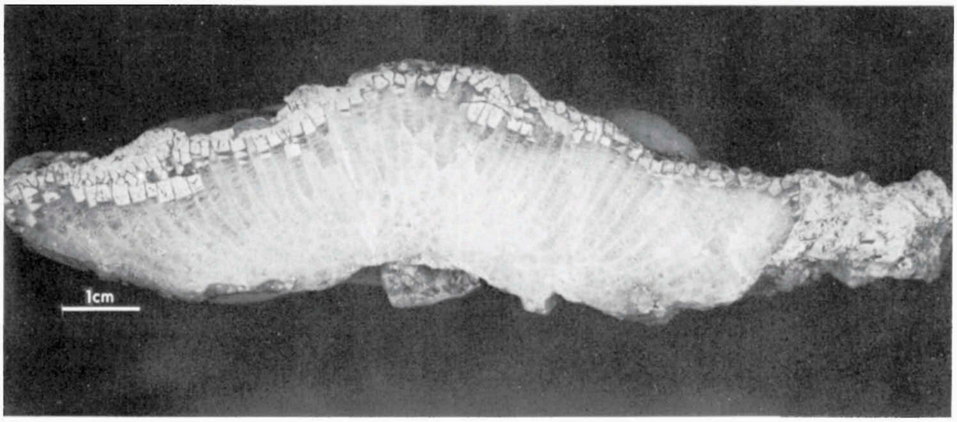

Fig. 18. Flattened colony of *Favosites forbesi* from Kättelviken 6 (RGM 243 685), overgrown by algae. For explanation see page 33.

Fig. 19. Detail of *Favosites forbesi*, depicted in Fig. 18.

Oklahoma. Solitary corals are absent in places where colonial rugose corals have been enveloped by *Archaeolithophyllum.* The majority of the alveolitid and favositid coenostea from the Hamra oncolite is partly or completely enveloped by stromatolitic laminae. These laminae are more frequently found around alveolitid than around favositid coenostea, probably because oblate ellipsoidal incrustive shapes dominate in alveolitids, whereas hemispheroidal, oblate ellipsoidal coenostea occur in favositids (Fig. 15). Oblate ellipsoidal coenostea of favositids are usually thicker than similar alveolitid coenostea (Fig. 16). Consequently, favositids probably were more elevated above the sea bottom than alveolitid colonies. Moreover, large hemispheroidal *Favosites forbesi* coenostea showing effects of erosion are only rarely found and if so, only partly covered by stromatolitic laminae. Similarly eroded *Favosites forbesi* coenostea, completely coated by algae, are preserved as oncoids. Competition is seen in some coenostea between tabulate sponges (favositids, alveolitids and theciids) and encrusting algae that construct stromatolitic laminae consisting of cemented sediment particles.

Stromatolitic laminae encrust peripheral parts (Fig. 17; A-C) of a *Favosites forbesi* colony. Usually, these encrusted parts correspond with zones of closely spaced tabulae throughout the colony. These parts, however, have been laterally overgrown again during growth. Apparently the sponge was more and more hindered as is seen by growth irregularities in the uppermost part of the colony (Fig. 17; C). At last it probably was completely overgrown by stromatolitic laminae and died. Later erosion sometimes carried away some of the stromatolitic crust.

A flattened colony of *Favosites forbesi* (Fig. 18) is overgrown by stromatolitic laminae. Although no irregularities are seen in the main part of the coenosteum, the uppermost part shows a remarkable growth pattern. Some areas died and the calicles were filled with sediment, but somewhat later they were rapidly overgrown from lateral intact parts of the colony (Fig. 18). No stromatolitic la-

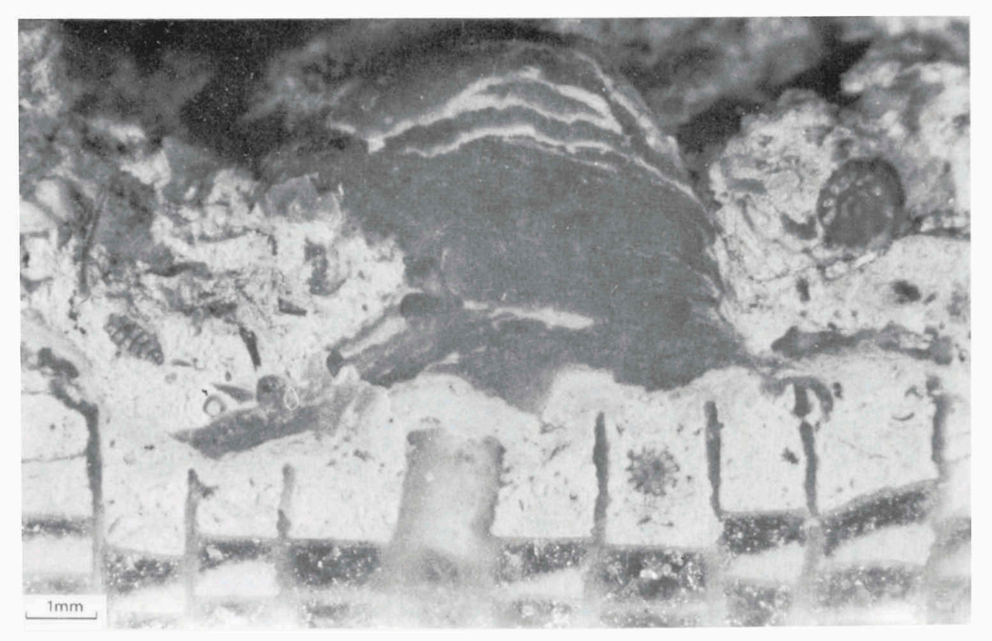

Fig. 20 Detail of *Favosites forbesi,* depicted in Fig. 18.

minae occur at these surfaces. The calicles are well preserved and show upward thinning of the calicle walls (Fig. 19). Tabulae are never found in top of the calicles. These areas of the colony did not die because of sedimentary or other abiotic factors, because localized dying of the colony seems improbably. Grazing organisms (gastropods?) possibly caused these irregularities within the coenosteum. The colony soon died entirely as is indicated by the thinness of the capping calicle layer. The coenosteum was eroded during some period of time because tabulae are found in top of the calicles and the wedging-out of the topmost parts of the calicle walls has completely vanished. The colony was encrusted by algae later on (Fig. 20). Stromatolitic laminae are not seen because of recent erosion in the left part of the colony.

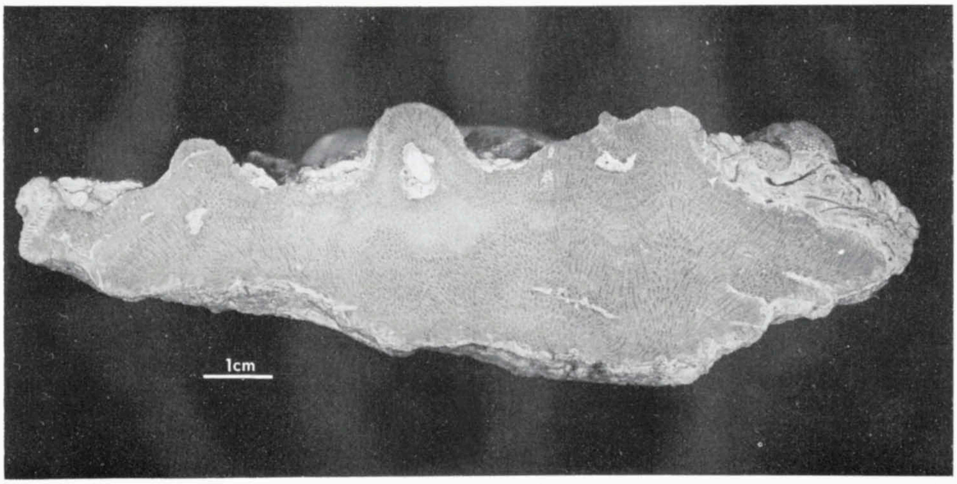

Fig. 21. Colony of *Alveolites suborbicularis* from Uddvide 2 (RGM 243 686), showing preferential growth towards the north-east. For explanation see page 35.

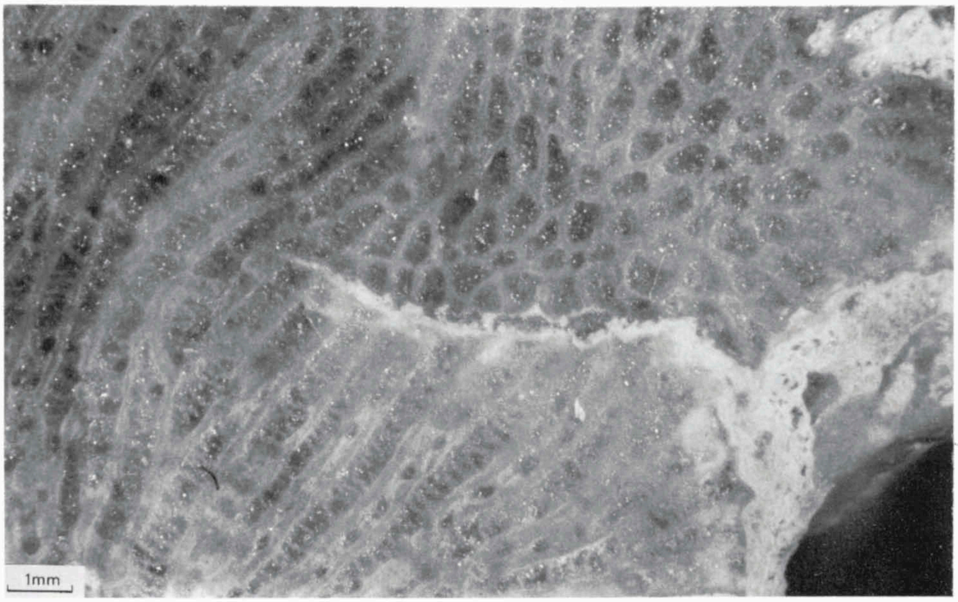

Fig. 22. Detail of *Alveolites suborbicularis*, depicted in Fig. 21.

Thin, buff bands within *Alveolites suborbicularis* coenostea (Fig. 21) roughly reflect morphological development during growth. The oblate ellipsoidal coenosteum started to grow as a thin ellipsoid. The main growth direction was towards the north-east whereas growth towards the south-west was limited by external factors such as current and/or wave action and competition by algae. These environmental parameters caused a vertical growth instead of a horizontal one. Peripheral parts of the coenosteum in the south-western part of the colony were regularly covered by stromatolitic laminae. These stromatolitic laminae were in turn overgrown again by the alveolitid (Fig. 22). At last algae encrusted almost the whole south-western part of the colony (Fig. 23) and growth was limited to more or less elevated parts. In this stage growth irregularities, caused by algal encrustrations, are also visible in the north-eastern part of the coenosteum. Al-

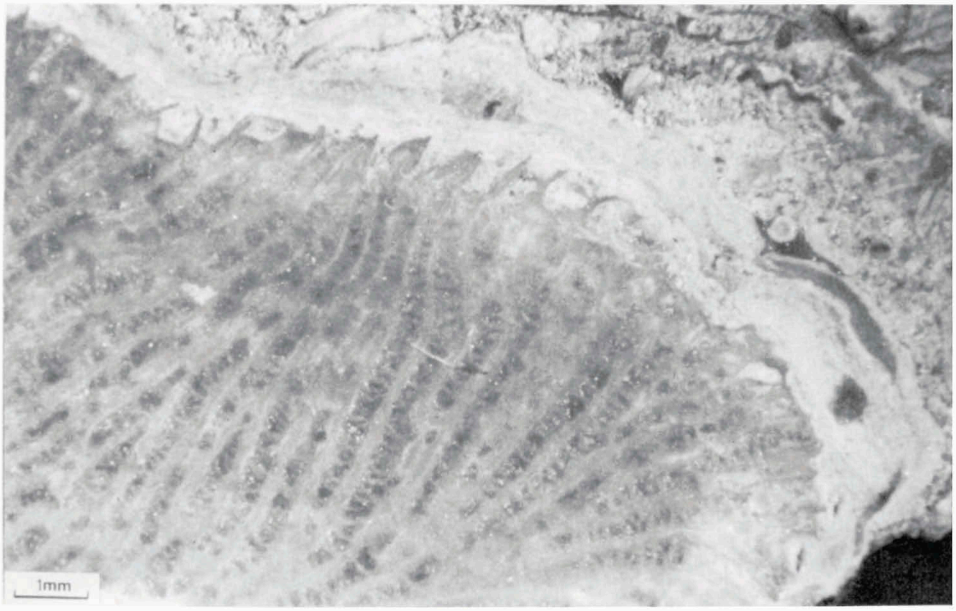

Fig. 23. Detail of *Alveolites suborbicularis,* depicted in Fig. 21.

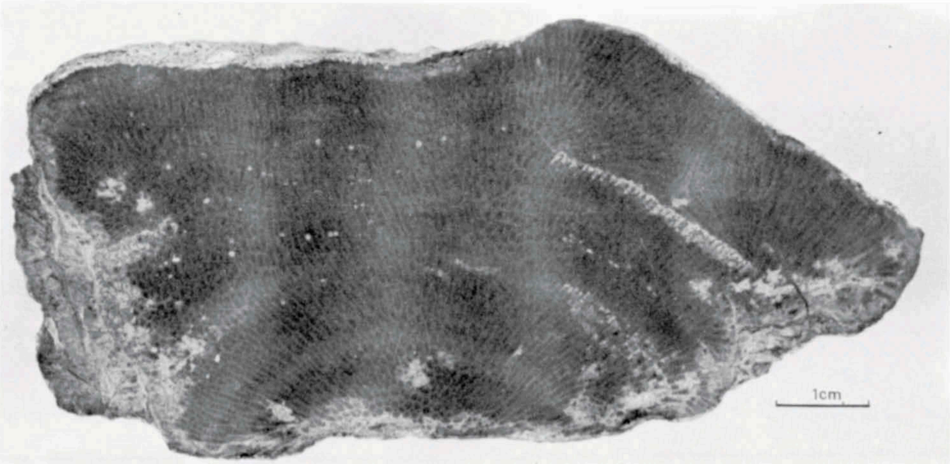

Fig. 24. Colony of *Alveolites suborbicularis* from Uddvide 2 (RGM 243 687), showing interaction of algae. For explanation see page 36.

though a continuous cover of stromatolitic laminae is not observed (recent erosion?) it is reasonable to suppose this *Alveolites suborbicularis* coenosteum was stifled by encrusting algae.

The colony depicted in Figure 24 started to grow as an oblate ellipsoid. This growth habit developed into a platy shape, probably because of algal competition and/or other environmental influences. A part of this coenosteum was encrusted by algae and later on laterally overgrown again. A growth pattern similar to that of *Reptomulticava multigemmata* (Hillmer, Goutier & Kinney, 1975) developed in this way.

The shape of *Thecia confluens* coenostea is distinctly determined by competition between *Thecia* and algae (Fig. 25). The calicle walls are thin in the basal part of an encrusting *Thecia confluens*. This indicates that the colony rapidly extended over its substratum (Stel, 1976). Calicle walls are very thick in the upper part, indicating a diminishing growth rate. This *Thecia confluens* specimen was later on partly overgrown by algae which in turn were recovered by the *Thecia*, starting with a zone of thin walled calicles again. This process was repeated several times.

SPONGE BIOSTROMES IN THE LOWER HAMRA-SUNDRE BEDS

Munthe (1921) noticed the occurrence of small sponge-biostromes within the Hamra oncolite near Kättelviken. Manten (1971) described a similar biostromal development at Grumpevik. The authors investigated sponge-biostromes at Kättelviken 6, Uddvide 1 (Fig. 26) and Rovald 3. Compared with the oncolite, the sponge-biostromes are characterized by a relatively large number of stromatoporoids. In a small collection from the sponge-biostrome at Kättelviken 6, the main reefbuilders were large coenostea (max. diameter 75 cm) of *Parallellostroma*

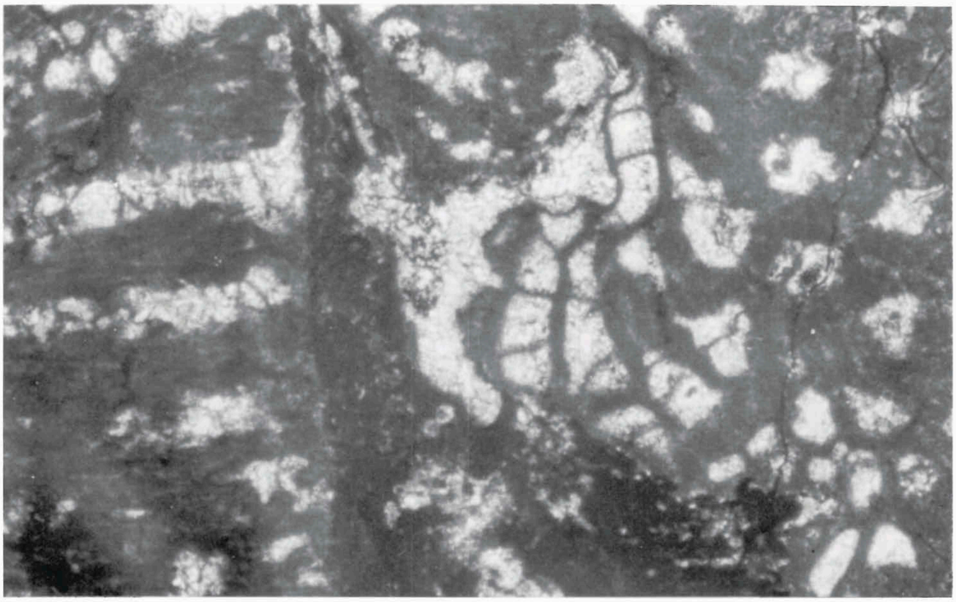

Fig. 25. Colony of *Thecia confluens* from Uddvide 2 (RGM 243 688), showing interaction of algae. For explanation see this page above.

typicum and *Lophiostroma schmidti* together with several flattened coenostea of *Favosites forbesi* and *Alveolites suborbicularis*. Less important are incrustive alveolitids and auloporids, thamnoporids, *Phaulactis* species, bryozoans, and brachiopods. The occurrence of *Leptaena rhomboidalis* indicates that the fauna is partly transported, just as in the oncolite. The epifauna of *Lophiostroma schmidti* mainly consists of auloporids and bryozoans. In contrast with ellipsoidal *Favosites forbesi* colonies found in between the oncoids, the flattened coenostea in the sponge-biostrome do not show competition between the former and algae. The favositids were coated by algae after death. Sponge-biostromes in the Hamra oncolite probably were scattered small circular or elliptical elevations. Their width was about 5-10 m, whereas their height probably was 0.1 to 0.5 m above the sea bottom.

Conclusions

A synthesis of the lithological and paleobiological interpretation yields a sedimentation model of the Upper Burgsvik and Lower Hamra-Sundre Beds, which is depicted in Figure 27. The sediments were predominantly deposited in a marine environment, although some elements (aragonitic, now neomorphic calcite, ooids and some *Girvanella* species which might have grown in a fresh water environment) indicate influences of brackish or fresh water. From north-west to south-east we see five main depositional environments: a beach environment (facies I), a lower fore-shore environment (facies II), a surf environment (facies III), a

Fig. 26. Sponge-biostrome in facies IV at Uddvide 1.

shallow marine current environment (facies IV), and an off-shore current or sometimes quiet environment (facies V). This succession of facies represents a transgression, following the regressive sequence of the foregoing Eke and Lower Burgsvik Beds. The tabulate fauna of facies IV is mainly composed of *Favosites forbesi* and *Alveolites suborbicularis.* The shape of these sponge colonies was determined by physical (current) and biological (intergrowth with algae) factors to a high degree.

The environmental interpretation and the study of outcrops enable a reconstruction of the coast line in Late Burgsvik and Early Hamra-Sundre times (Fig. 28).

We have tried to fit this reconstruction in a paleogeographical map of the Baltic region of that time. Figure 29 shows the paleogeography of the Baltic epicontinental sea during Ludlovian times. The 'Ludlow Baltic' was an embayment connected with the sea of the Variscan Geosyncline in the south (Kaljo, 1970; Sokolowski, 1970; Walter, 1972). An area of carbonate deposition was situated in the eastern part of this embayment, whereas terrigenous sedimentation of silt and clay occurred in the western and central part. There might have been a connection between the 'Ludlow Baltic' and the Caledonian Geosyncline in the north as well.

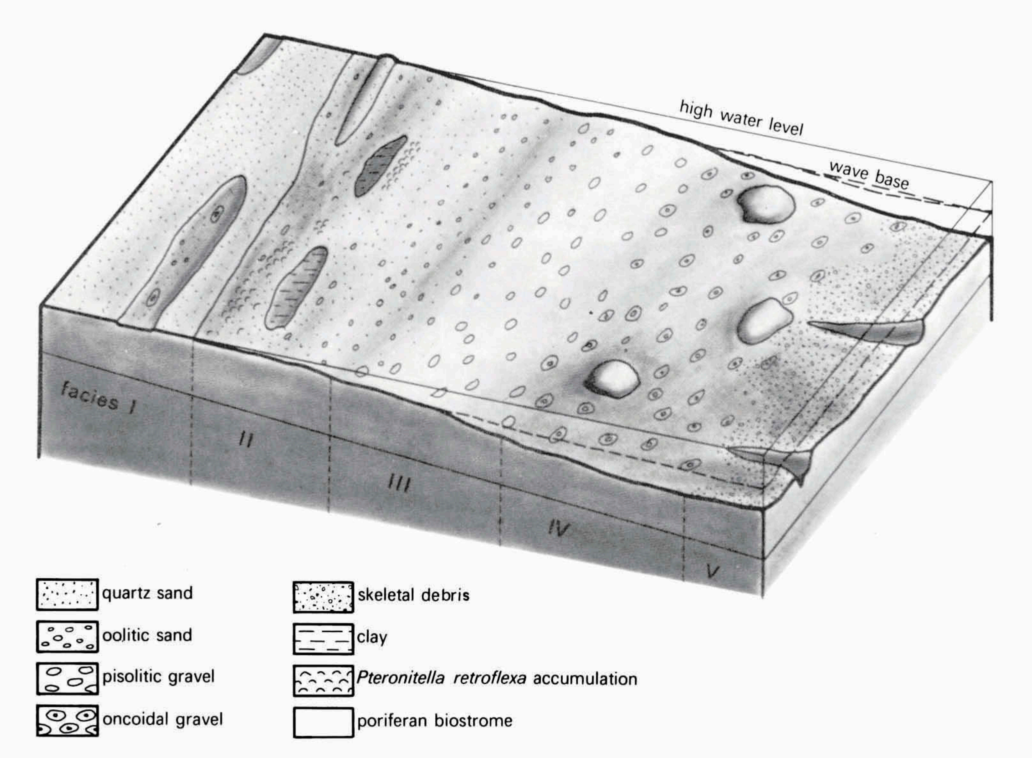

Fig. 27. Facies model of the Upper Burgsvik and Lower Hamra-Sundre Beds.

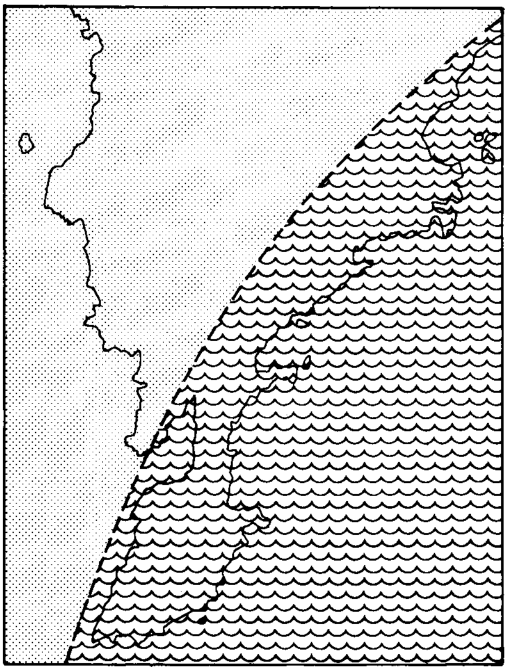

Fig. 28. Reconstruction of the coastline during Late Burgsvik and Early Hamra-Sundre times.

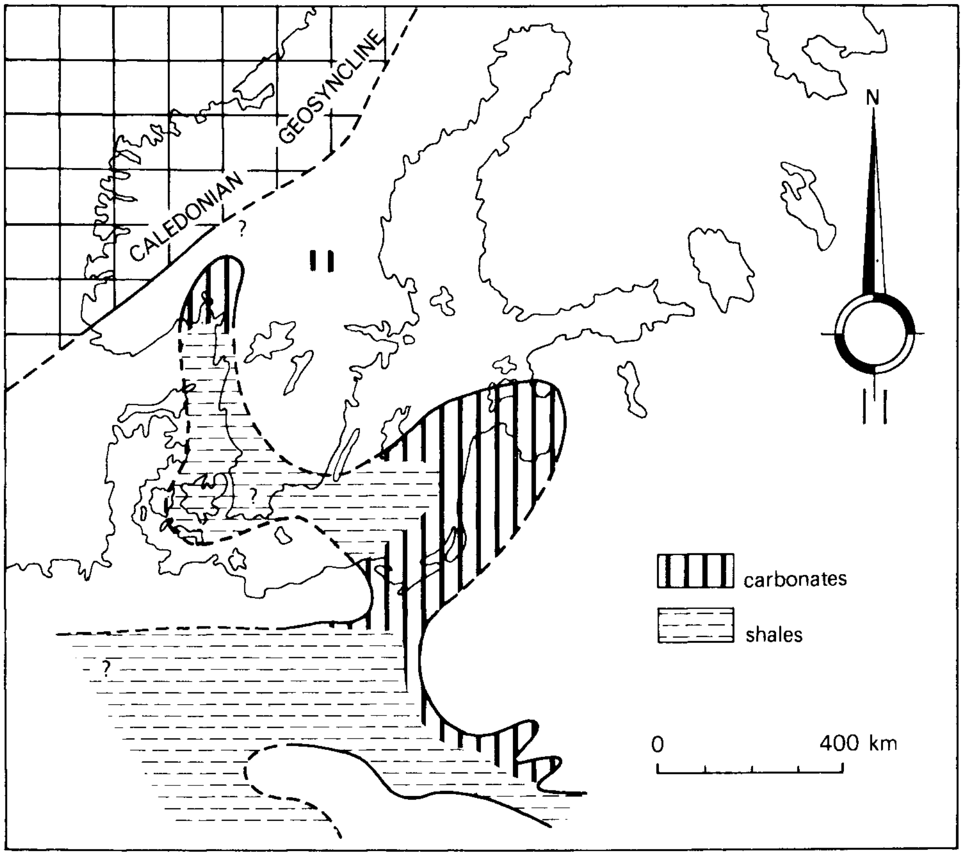

Fig. 29. Tentative paleogeographic map of the 'Ludlow Baltic'. The map is compiled after Kaljo, 1970; Sokolowski, 1970; and Walter, 1972.

Appendix

Seven new localities are described conform the 'Reference localities for palaeontology and geology in the Silurian of Gotland' of Laufeld (1974a).

FIDE 1, CJ 5205 2965, c. 700 m SSW of Fide church. Topographical map sheet 5I Hoburgen NO & 5J Hemse NV (med röda vägar). Geological map sheet Aa 152 Burgsvik. Surface exposure in a meadow, c. 59 m W of the road.
Burgsvik Beds and Hamra Beds.

HUSRYGGEN 4, CJ 2685 1515, c. 2110 m WNW of Sundre church. Topographical map sheet 5I Hoburgen SO & 5J Hemse SV. Geological map sheet Aa 152 Burgsvik. Abandoned quarry about 10 m W of the road, c. 850 m S of the house at Klasens. The section of Husryggen 4 was taken SW of a small road leading down to the beach.
Reference level: the highest massively bedded sandstone bed below the first accumulation of *Pteronitella retroflexa* valves.
Burgsvik Beds: uppermost part.

KÄTTELVIKEN 6, CJ 2725 1540, c. 1950 m NW of Sundre church. Topographical map sheet 5I Hoburgen SO & 5J Hemse SV. Geological map sheet Aa 152 Burgsvik. Section in the upperpart of the cliff immediately W of the road, c. 520 m S of the house at Klasens.
Reference level: the Burgsvik-Hamra boundary.
Burgsvik Beds: uppermost part.
Hamra Beds: unit a.

KÄTTELVIKEN 7, CJ 2715 1532, c. 1950 m NW of Sundre church. Topographical map sheet 5I Hoburgen SO & 5J Hemse SV. Geological map sheet Aa 152 Burgsvik. Cliff section on the beach c. 600 m S of the house at Klasens.
Reference level: highest massively bedded sandstone bed.
Burgsvik Beds: uppermost part.

KAUPARVE 2, CJ 5835 3567, c. 4650 m SE of Gröttlingbo church. Topographical map sheet 5I Hoburgen NO & 5J Hemse NV (med röda vägar). Geological map sheet Aa 152 Burgsvik. Ditch, c. 750 m ENE of Kauparve, along the W side of the road to Nybro.
Hamra Beds: unit a.

KULHAKEN 1, CJ 3020 2280, c. 5350 m NNW of Vamlingbo church. Topographical map sheet 5I Hoburgen SO & 5J Hemse SV. Geological map sheet Aa 152 Burgsvik. Section 20 m SSW of a small road leading to an abandoned quarry near the sea shore, c. 750 m SSW of the triangulation point at Kulänge.
Reference level: the highest massively bedded sandstone bed.
Burgsvik Beds: uppermost part.

MUNKBOUDD 1, CJ 2920 1835, c. 2600 m WNW of Vamlingbo church. Topographical map sheet 5I Hoburgen SO & 5J Hemse SV. Geological map sheet Aa 152 Burgsvik. Shore exposure, partly overgrown.
Burgsvik Beds: uppermost part.

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