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COMPOSITION, STRUCTURE AND ENVIRONMENTAL SETTING OF SILURIAN BIOHERMS AND BIOSTROMES IN NORTHERN EUROPE

ROBERT RIDING
Department of Geology
University College
Cardiff, United Kingdom

ABSTRACT

Silurian reefs of northern Europe occur in cratonic sedimentary sequences which have been relatively well documented stratigraphically and paleontologically although the reefs have generally been less closely examined than the level bottom communities. Reef development adjacent to the Caledonian Belt was restricted by siliciclastic sedimentation and this is also reflected in the low proportions of carbonate rocks in the Welsh Borderland and Oslo successions. Marine sequences in the Baltic areas of Gotland and Estonia are relatively thin and contain much higher proportions of both carbonates and reefs.

Four main types of reef are recognizable on Gotland. Axelsro (previously termed Upper Visby) and Hoburgen Reefs are essentially tabulate coral and stromatoporoid dominated bioherms of moderate to high diversity. Their dense structure and argillaceous matrix made them locally unstable and prone to marginal collapse and internal displacement. Important accessory reef builders include rugose corals, calcareous algae, *Problematica*, and bryozoans. Similar bioherms, particularly of the smaller tabulate rich Axelsro type, are well developed in the Wenlock Limestone of the Welsh Borderland of England where good examples occur at Wenlock Edge. They are also present in the Oslo Region of Norway, together with tabulate dominated biostromes and *Rothpletzella-Wetheredella* bioherms, and occur at several horizons, sometimes very extensively, in the Llandovery and Wenlock.

In Gotland, Hoburgen reefs are especially widespread at numerous horizons, but a unique feature is the occurrence of Kuppen and Holmhällar type stromatoporoid biostromes which have rigid dense to frame structures and relatively low diversity. They are interpreted as shallow water, high energy linear reefs which developed preferentially in the cratonic interior.

The Estonian Silurian sequence shows close similarities to that in Gotland. Reefs are developed at a number of horizons but are generally little documented in detail.

Reef geometry and organic composition were controlled by environmental factors. The size and morphology of the organisms in turn determined the internal structure of the reefs. The bioherms show internal displacement and differential compaction of adjacent sediments in response to their own weight and to subsequent overburden. The biostromes behaved more rigidly and compaction was taken up mainly by stylolitization of adjacent large skeletons.

INTRODUCTION

The Silurian successions of Britain, Scandinavia and the Baltic contain organic reefs which are among the best examples of their age in the world. They are constructed primarily by stromatoporoids and tabulate corals, together with calcareous algae, bryozoans and rugose corals, and are well developed in four areas: 1. Welsh Borderland of England, 2. Oslo Region of southern Norway, 3. Swedish island of Gotland in the Baltic Sea, and 4. western Estonia, particularly the islands of Hiiumaa and Saaremaa (Fig. 1). Most of these reefs are biohermal but biostromes also occur, some of which may represent fringing or barrier-reefs.

These areas have attracted geological interest for up to 150 years and all have been the objects of detailed studies: by Murchison (1839) on the Welsh Borderland, Kiaer (1908) on the Oslo Region, Hede (1925–1940) on Gotland, and Kaljo and his co-workers (1970, 1977) on Estonia and the subsurface of Latvia and Lithuania. The occurrence of reef like bodies in these rocks has long been recognized, even though their origin was at first uncertain. As early as 1914 Crosfield and Johnston had noted their similarity at widely separated locations and were comparing examples of them in England, Norway, Gotland and North America.

Despite these studies, and their seminal influence on subsequent research, much still remains to be learned about these bioherms and biostromes and their settings. Significant stratigraphic problems remain in the Oslo and Gotland areas, and the reefs of the Oslo Region have hardly been described. But the intensive stratigraphic and paleontologic documentation which has been carried out, coupled with detailed studies of reefs at Wenlock Edge in England and on the island of Gotland, provide strong incentive for further paleoecologic and sedimentologic analyses of the reefs and their associated facies.

FIG. 1.—Silurian outcrops (stippled) and localities in northern Europe outside the Caledonian mobile belt and the position of the Upper Silurian Oslo-Scania-Baltic Basin (syneclise, cross-hatched).

The Silurian sediments of the Anglo-Baltic area accumulated on the European craton during flooding prior to the conclusion of the Caledonian orogenic cycle. At the continental margin, in western Britain and Norway, deeper water sediments were deposited and this linear belt developed into a zone of more rapid sedimentation and then deformation as the orogeny progressed. The essentially cratonic situation of each of the four main reef bearing areas is reflected by the relative thinness of their rock sequences and their lack of deformation compared to the continental margin, but they also show some distinct differences produced by their situations relative to the craton margin and interior. The reefs of the Welsh Borderland and Oslo regions formed close to the shelf-edge along the southeastern margin of the Iapetus Ocean and their development, particularly in southern Norway, was restricted by siliciclastic sedimentation from adjacent areas of uplift. In contrast, the Baltic area, which was distant from the mobile belt, shows a wider range of reef types over a longer period of development.

All four areas contain a diverse and well preserved shelf biota in the pale buff to green-grey shales and argillaceous limestones commonly associated with the reefs. It is the excellent preservation of these rocks and their enclosed fossils which enabled Roderick Murchison during the 1830's and 1840's to establish within them the classic sections of the Silurian System. Although Murchison noted the presence of the reefs in Britain and Scandinavia during his extensive travels he at first mistook their nature and regarded them as concretionary bodies. It was Charles Lyell, in 1841, who first recognized their organic nature at Wenlock Edge in England, at about the same time that James Hall was comparing the newly discovered Niagaran reefs of the Great Lakes region with Recent coral atolls.

More than a century of subsequent research has refined and extended Murchison's work, establishing the stratigraphic framework of the Silurian of northern Europe and, in the process, documenting the geological setting of the enclosed reefs in great detail. However, this emphasis on stratigraphy and stratigraphic paleontology has not focussed much attention on the reefs themselves. Although a number of valuable studies have elucidated details of some of the reefs, many aspects of their composition, distribution and origin remain unclear. Even since the upswing in interest in carbonates and paleoecology in the early 1960's few studies have specifically dealt with the reefs in detail. Silurian paleoecologic studies of the past 10–15 years have concentrated upon level bottom marine communities and even Manten's (1971) extensive documentation of the Gotland reefs deals primarily with the form and distribution of the reefs rather than with their internal composition and structure.

For these reasons a mere review of the published accounts of the bioherms and biostromes would be of limited value. For this paper I have attempted to go further than previous workers in drawing comparisons between the Welsh Borderland, Oslo and Baltic areas, and also in providing details of reef structure and composition, particularly on Gotland. But the reefs are extensive, the subject complex and most of my contribution is only preliminary to further studies. In Britain and Norway, in particular, I have added little to previous work. Considering its relatively small extent the Wenlock Edge area is the most intensively documented site so far as bioherms are concerned and I have drawn mainly upon the studies by Terence Scoffin and Brian Abbott. The reefs of the Oslo Region are much less well known and I have relied heavily in this account upon information kindly supplied by Nils Martin Hanken, Snorre Olaüssen and David Worsley who are currently working in this area. Gotland contains the finest and most extensive development of Silurian reefs in Europe, and probably in the world, and I have concentrated most attention upon it in this review. Estonia is the one area which I have not visted and I have drawn information solely from the recent volumes edited by Dmitri Kaljo.

The term *reef* continues to convey so many different things to different people that I should say here that I am using it as a general term for any essentially in-place accumulation of carbonate skeletons and associated organically localized material. Much discussion of the nature of reefs has revolved around the problems of interpreting the original environment and strength of the structures, and has proceeded from attempts to discriminate between them on the basis of criteria which are thoroughly subjective. Reefs are com-

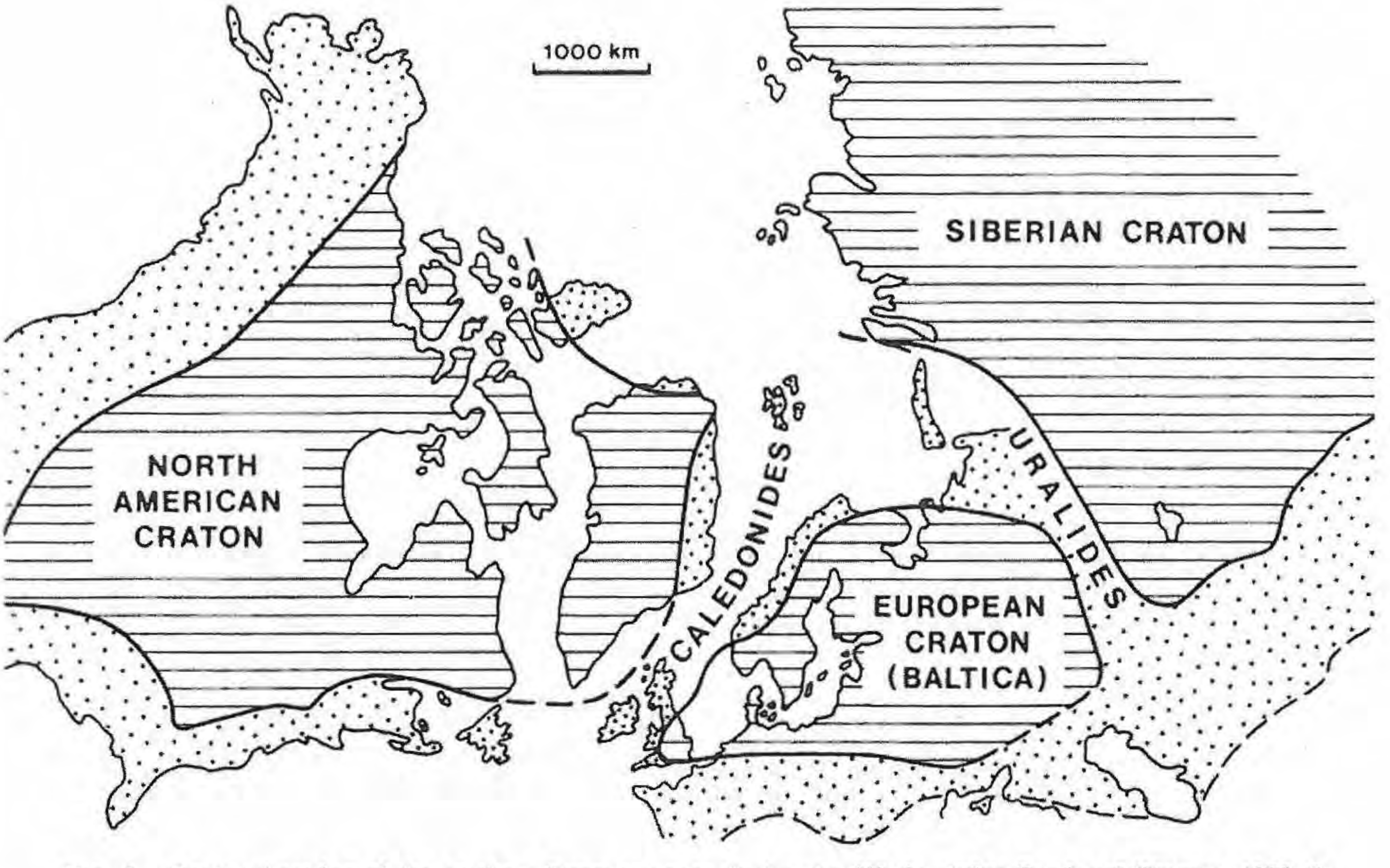

FIG. 2.—Regional setting of the northern European area during the Silurian (after Read and Watson, 1975, fig. 2.1; Ziegler *et al.*, 1977, fig. 2).

positionally and structurally diverse, but they nevertheless share a group identity. Here I attempt to describe the main skeletal components of all the reefs mentioned and to indicate wherever possible their internal structure in simple terms (dense, frame, *etc.*; Riding, 1977). Stromatoporoid morphotypes follow Kershaw and Riding (1978).

REGIONAL SETTING

Current reconstructions of the northern European region during the Silurian show a triangular continent situated between North America and Siberia and lying close to the equator. It was separated from these continents by two narrow linear seaways to the west and east (Ziegler *et al.*, 1977; fig. 2) whose margins represented the Caledonian and Uralian mobile belts respectively (Fig. 2). This European continent (Baltica of Ziegler *et al.*, 1977) appears to have been a single cratonic unit, although during the latter part of the Silurian a linear basin (the Oslo-Scania-Baltic Syneclise) developed between the Oslo and southern Baltic areas, passing through southern Sweden and possibly linking with the Rheic Ocean to the south (Størmer, 1967, fig. 22).

Late Ordovician regression, perhaps related to glaciation, exposed the continent but it was progressively flooded during the early Silurian and this produced extensive epicontinental shelf seas, with embayments and islands, which covered much of the western surface (Fig. 1). Land remained to the east, over much of what is now Russia almost as far as the Urals, probably throughout the period (Kaljo, 1972).

A mixed carbonate-siliciclastic sequence accumulated on the shelf and is generally less than 1 kilometer thick, except in the Oslo-southern Baltic Trough where it reaches 2 kilometers. The proportions of limestone, mudstone-shale, and sandstone-conglomerate in the sequence vary with position on the shelf (Fig. 3). The Oslo-southern Baltic Trough succession is dominated by mudstones and shales but in Gotland and Estonia, 300–500 kilometers to the northeast, the Llandovery-Ludlow sequence is only 0.5 kilometer thick and carbonate rocks represent 50–75 percent of the total succession. These Baltic areas were in the cratonic interior, remote from sources of siliciclastic detritus. There are only a few thin sandstone units in the Gotland succession, but the proximity of the area to land at this time is emphasized by the presence of disconformities in the sequence, which often truncate reef bodies and result in a thin sequence which totals only approximately 450 meters from upper Llandovery

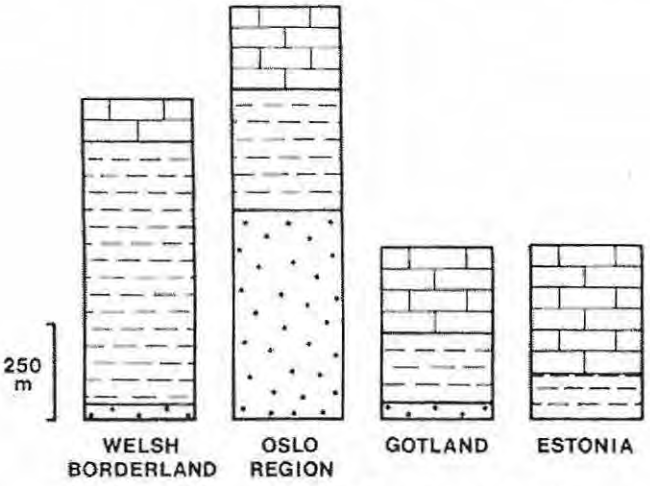

FIG. 3.—Thicknesses of Llandovery-Ludlow sequences in the four areas of reef development showing the proportions of sandstone, shale and limestone/dolostone in each. Note the thinness of the Gotland-Estonia sequences and the relatively high proportions of carbonate rocks they contain.

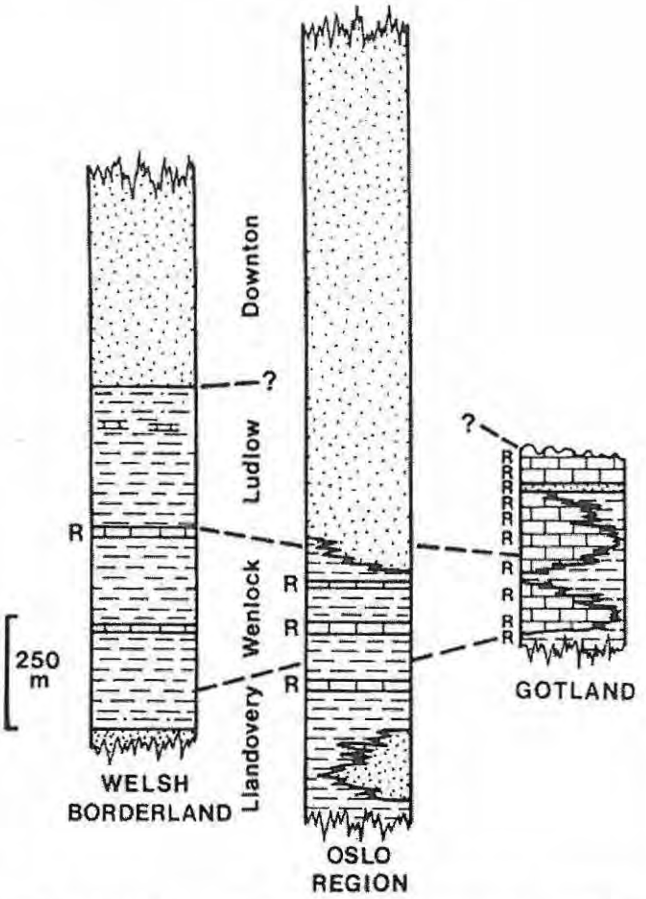

FIG. 4.—Schematic Silurian sequences in northern Europe showing how reef horizons (R) are distributed in time and space relative to lithofacies.

to upper Ludlow. Both the Gotland and Estonian sequences were deposited in a broad embayment with the Oslo-Baltic Trough to the south and land to the northwest, north and east (Fig. 1). The fineness of the siliciclastic sediment indicates that runoff was low, probably due in part to reduced relief on the land area.

In contrast, the Welsh Borderland and Oslo region have Llandovery-Ludlow sequences approximately 1 kilometer thick in which carbonates represent less than 20 percent of the succession. These western areas were close to the shelf-edge and to the mobile belt and carbonate deposition was constrained by either siliciclastic influx or deep water, or both. The Oslo region experienced influx of coarse siliciclastic sediment reflecting periods of uplift to the northwest (Størmer, 1967, p. 204–207) caused by gradual closure of the Iapetus Ocean. The most important of these were during the Llandovery and the Ludlow. Sandstones and conglomerates comprise approximately 50 percent of the Llandovery-Ludlow sequence which attains a thickness of approximately 1100 meters near Oslo. The Welsh Borderland area was also close to the continental margin but it did not receive coarse sediment influxes from the mobile belt until the Downton. Prior to that a dominantly shale-siltstone sequence about 850 meters thick accumulated in which limestones represent approximately 13 percent and sandstones only 5 percent of the total.

These differences in regional position and sedimentation are directly reflected in the degree and duration of reef development. Reefs in the Welsh Borderland only occur at a single horizon, in the upper Wenlock. In the Oslo region they occur at several levels in the Llandovery and Wenlock, and in Gotland and Estonia there are examples of reefs in the Llandovery, Wenlock and Ludlow (Fig. 4).

In keeping with its intra-cratonic situation the Baltic succession is virtually unaffected structurally. The regional dip on Gotland is only one or two degrees and reef-bearing units can be traced continuously for up to 60 kilometers in coastal cliffs. The Welsh Borderland sequence shows more tectonic influence but is still well preserved and structurally simple. At Wenlock Edge the strata are tilted at 10 degrees to the southeast, and at several other locations in the area reefs occur in small faulted and upfolded areas influenced by both Caledonian (Siluro-Devonian) and Hercynian (Carbo-Permian) deformation. The Oslo Region is the most complex of the areas due to Caledonian folding combined with widespread normal faulting related to extensional rifting of the area during the Late Paleozoic. These effects hamper correlation but the rocks are nonetheless relatively well preserved.

When Murchison visited the Oslo Region in 1841 he assumed that the reef limestones there were of the same age as those in the Welsh Borderland and, similarly, that the non-marine sandstones were of Downton age. Aspects of this error of equating facies similarity with time equivalence have persisted to the present in some areas. Workers in Scandinavia have tended to adhere to long established stratigraphic divisions which combine features of both lithostratigraphic and biostratigraphic units. These divisions, termed topostratigraphic units have been employed in the Oslo and Gotland sequences and possess a broad basic utility. But they necessarily suffer fundamental weaknesses of lithologic heterogeneity on the one hand and diachronism on the other, and it will remain difficult to confidently assess the detailed paleoenvironmental setting of reefs in parts of these successions until they are revised.

Attempts to analyze the patterns of relative sea level movements during the Silurian in northern Europe have confirmed basic trends but have also led to differences in opinion concerning both the timing and cause of smaller scale events. The basic pattern in all four areas is a Llandovery transgression and a regression during the Ludlow. These appear to have been prolonged eustatic changes in sea level probably related to glaciation or global tectonism, or both (McKerrow, 1979, p. 142). In the Welsh Borderland sea level fall during the late Wenlock promoted reef development in the Wenlock Limestone and this was terminated by renewed deepening during the basal Ludlow. Hurst (1975) and McKerrow (1979, fig. 1) recognize a basal Ludlow transgression as a general feature over northern Europe, but Bassett (1976) argues against this view on the grounds that "many sequences in the Anglo-Baltic area suggest widespread regression and not transgression at this level (e.g. Pembrokeshire, Norway, Estonia)" (Bassett, 1979, p. 144). He believes that the deepening at the Wenlock-Ludlow boundary in the Welsh Borderland is a local, tectonically controlled effect. There is no doubt that reef development in all these areas is closely related to water depth and rate of siliciclastic sedimentation and distinct phases of carbonate deposition and reef formation characterize the Baltic sequences. But the degree of correlation between these has still to be established and this is dependent largely upon clarification and correlation of stratigraphic units in Scandinavia and the Baltic.

Northern Europe during the Silurian belonged to the North Silurian faunal realm (Boucot, 1974). Although provincialism gradually increased during the period the Silurian was generally a time of marked faunal homogeneity. Probably this was strongly influenced by global climate and the widespread epeiric seas of the time. Northern Europe (Baltica) occupied an equatorial situation and Ziegler *et al.* (1977, p. 40–41) deduce a tropical, mainly moist climate for Baltica during the Silurian. Gradual regression towards the end of the period enhanced provincialism and also stimulated reef development in areas remote from sources of siliciclastic sediment. Continental conditions were established over the whole area during the late Silurian.

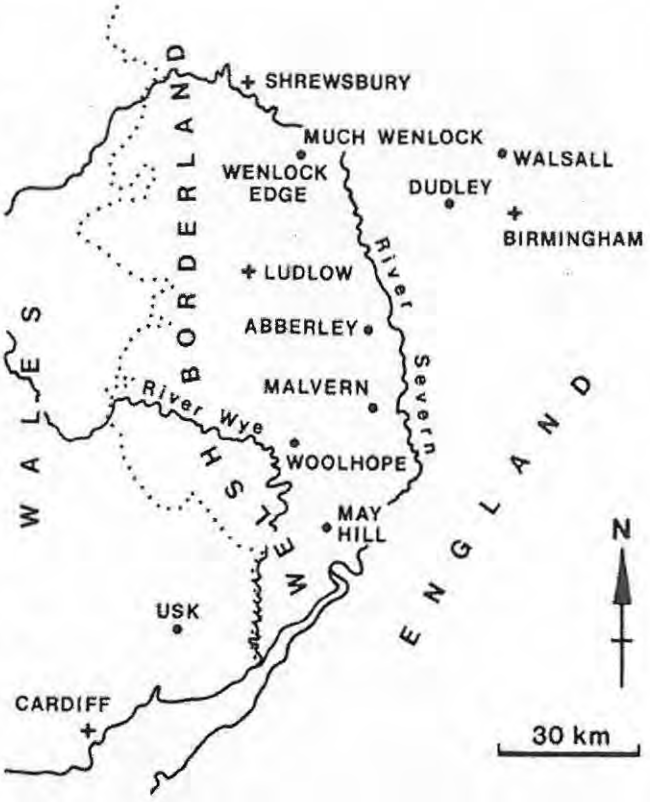

FIG. 5.—Reef localities in the Welsh Borderland.

Welsh Borderland

The area lying between the English Midlands and Wales is one of the classic regions of British geology. It is dominated by Middle Paleozoic sedimentary rocks and represents the eastern part of the district selected by Murchison (1839) as the type area for the Silurian System. Reefs occur at only one horizon: in a relatively thin carbonate unit, at or near the top of the Wenlock Series, which is known generally as the Wenlock Limestone. Barrier-reefs have been suggested to occur in the area of Wenlock Edge (Symmonds, 1872), but present exposures indicate that only patch-reefs occur. These have been referred to by quarrymen as "ballstones" or "crog-balls" in reference to their massive and irregularly lensoid form, and they have been preferentially mined because of their purity relative to the enclosing argillaceous limestones.

The Wenlock Limestone is never more than 150 meters thick and often, as at Wenlock Edge, it is only 20–30 meters, but it has a wide occurrence over the triangular tract of country between

FIG. 6.—Aerial view to southwest along Wenlock Edge from near Much Wenlock. The line of the escarpment is offset by faults. Photograph from Cambridge University Collection, copyright reserved.

Shrewsbury, Birmingham, and Cardiff and, although it is often very argillaceous, bioherms are known to occur within it at Wenlock, Dudley, Walsall, Abberley, Malvern, Woolhope, May Hill, and Usk (Fig. 5). These localities can all be regarded as being in the Welsh Borderland area except for Dudley and Walsall which are part of the West Midlands conurbation around Birmingham.

The Wenlock Limestone is sandwiched between thick shale-siltstone units; the Wenlock Shale below and the Elton Beds, of Ludlow age, above. These sediments comprise the middle part of a Silurian shelf sequence and were deposited relatively uniformly over the whole region following transgression from the west during the Llandovery (Ziegler, 1970, p. 456–459). The Llandovery-Ludlow sequence on the shelf is approximately 850 meters thick. During the early Wenlock land lay 100–150 kilometers to the southeast and south of the Wenlock Edge area, with basinal facies marking the shelf-edge only 20 kilometers to the west (Bassett, 1974, fig. 7). Siltstones, calcareous shales and thin nodular limestones, constituting the lower part of the Wenlock Shale, were deposited in the northwestern part of the region, including Wenlock Edge, Dudley and Walsall. Towards the southeast argillaceous and bioclastic non-reef limestones (Woolhope Limestone) up to 60 meters thick were formed. In late Wenlock times limestone deposition with reefs (Wenlock Limestone) replaced argillaceous sedimentation over the entire region east of Usk, Ludlow and Wenlock. The basin margin remained in much the same position as earlier but continued transgression had extended the shelf sea southeastwards. Reef development was greatest between Wenlock and Dudley in the northern part of the area. Fewer, smaller bioherms formed in the Usk-Malvern area which was situated closer to the southern land mass. The Elton Beds, which conformably overlie the Wenlock Limestone at all localities where bioherms occur, mark a return to fine-grained siliciclastic shelf sedimentation. In this context the Wenlock Limestone represents a pause in siliciclastic sedimentation and shallowing of the shelf probably related to a regression (Scoffin, 1971, p. 212), followed by continued deepening during the early Ludlow (Hurst, 1975; Bassett, 1976). Major regression during the late Ludlow was followed by the start of Old Red Sandstone molasse sedimentation during the Downton (Pridoli).

At Wenlock the strata dip 10 degrees to the southeast and the Wenlock Limestone forms an escarpment, Wenlock Edge, between the River Severn and River Onny. The other bioherm localities, which are all to the east and south, occur in small upfolded or upfaulted inliers. Intensive quarrying and mining of the limestone at Dudley, although now discontinued, has left good exposures, particularly at Wren's Nest Hill. Wenlock Edge, 35 kilometers to the west, continues to be the site of extensive quarrying. Since these two localities are also in areas of good reef development they are now the best sites for examining the bioherms, and Wenlock is easily the better of the two, a fact indicated by the concentration of reef studies there in recent years. At present most outcrops further south in the Welsh Borderland are poor exposures in long disused quarries.

Wenlock Edge.—The outcrop formed by the Wenlock Limestone near Much Wenlock in Shropshire (where it has been renamed the Much Wenlock Limestone Formation by Bassett *et al.*, 1975) is generally less than 1 kilometer wide and it forms the 30 kilometers long Wenlock Edge (Fig. 6). It thickens northeastwards from 21 meters near the River Onny to 29 meters near Much Wenlock. Bioherm development is restricted to the area northeast of Easthope (Fig. 7) and consists of numerous relatively small patch-reefs (Fig. 8). Murchison (1833) described the succession in this area and noted "beds in Wenlock Edge contain many concretions of very great size and of highly crystalline structure" (p. 475).

In 1839 Murchison published his famous trea-

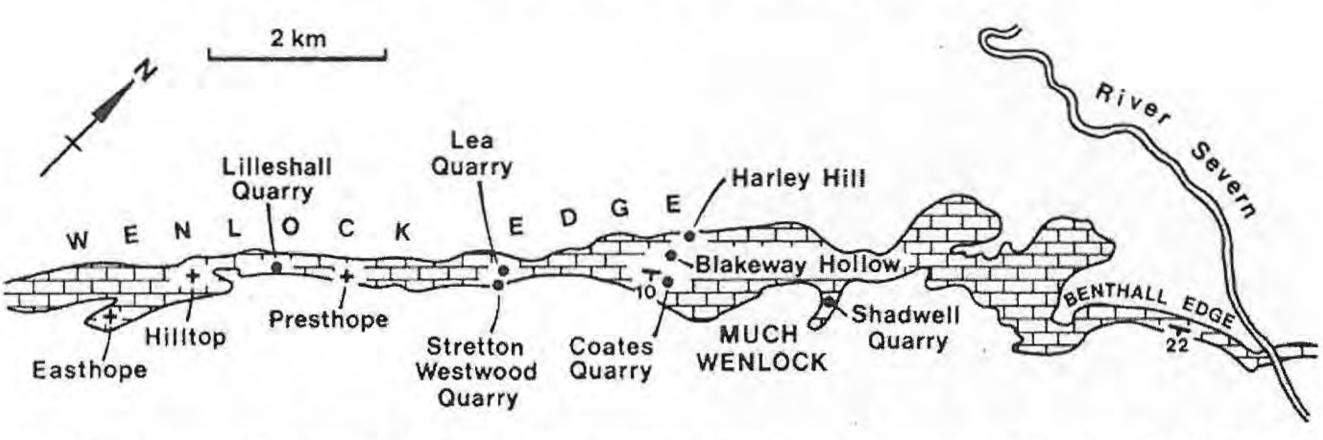

FIG. 7.—Outcrop of the Wenlock Limestone along the northeastern part of Wenlock Edge, England (after Bassett *et al.*, 1975, fig. 8).

tise on "The Silurian System" and added more details about the Wenlock Limestone. He regarded the massive irregular "ballstones," enclosed by argillaceous limestones and shales, as concretions formed by solidification or crystallization and noted that "where these concretions are prevalent, the strata undulate or are contorted." He was impressed by their size: "In one quarry recently opened (called the Yell), the small concretionary beds dip on the one side to the north, on the other to the southeast, and the center of the hill consists of one massive ballstone, which when I visited the spot, was laid bare to a depth of about *eighty feet*! the surface alone being covered with a few thin nodular beds. The exact width of this mass of ballstone had not been proved when I last visited these quarries, but it is doubtless very great, and must be of considerable value on account of its superior quality and accessible position" (p. 211).

Prestwich (1840) supported the concretionary hypothesis but Lyell (1841) noted the corals which they contained and became the first person to interpret them as organic structures. The corals and stromatoporoids of these bioherms were described by Edwards and Haime (1855) and Nicholson (1886–1890) respectively. Crosfield and Johnston (1914) give an excellent account of the "ballstones" at Wenlock Edge. They emphasize that "over 90 percent of the corals and stromatoporoids are found to be in position of growth in ballstone, while only 16 percent are in position of growth in the adjacent stratified rocks" and conclude, "Ballstone rock is the relic in place of large coral and stromatoporoid colonies still in the positions in which they originally grew" (p. 221). Hill (1936) briefly comments on the bioherms, which by then were generally regarded as coral reefs. The geology of the area has been described by Davidson and Maw (1881), Pocock *et al.* (1938), Whittard (1952), Greig *et al.* (1968), Holland *et al.* (1969), Hains (1970), Shergold and Bassett (1970), and Bassett *et al.* (1975). Several unpublished theses have dealt specifically with the paleoecology and sedimentology of the reefs at Wenlock Edge (Colter, 1957; Scoffin, 1965; Abbott, 1974) and have resulted in publications by Scoffin (1971, 1972), and Abbott (1976).

Southwest from Benthall Edge bioherms increase in size and number towards Easthope (Fig. 9). Scoffin (1971, fig. 1) gives an impression of barrier-type development at Hilltop where 80 percent of the upper 17 meters of the Wenlock Limestone consists of reef rock, compared with 25 percent near Much Wenlock and 10 percent at Benthall Edge. Bioherms do occur 1 kilometer southwest of Hilltop (Greig *et al.*, 1968, p. 179) but they are very small, less than one meter across, and there does appear to be a dramatic reduction in reef development near Easthope.

Shergold and Bassett (1970, p. 118–125) and Scoffin (1971, p. 180–183) distinguished a number of off-reef and inter-reef facies in the limestone, most of which are based upon rock types recognized by the quarrymen. They are essentially variations on nodular argillaceous limestones and crinoidal limestones and are illustrated by Shergold and Bassett (1970, figs. 4–13). The inter-reef beds show a coarsening upward sequence through the following lithofacies (Fig. 9):

A. thin-bedded nodular limestone-shale alternations, quarrymen's "Bluestone"; and
B. nodular shaly limestones, quarrymen's "Jack's Soap"; the limestones are argillaceous crinoid wackestones in both these lithofacies. B is a more shaly variety of A;
C. medium-bedded crinoid limestones, quarrymen's "Measures"; crinoid packstone-wackestones;
D. coarse thin-bedded crinoid limestone, quarrymen's "Gingerbread"; crinoid grainstones.

Grain-size, grain-support and sparry calcite increase upwards generally through these inter-reef facies, but lateral and vertical distribution of them is nevertheless quite variable. Facies A shows a

FIG. 8.—Small lensoid bioherm in the Wenlock Limestone, 3 kilometers northeast of Much Wenlock, England.

gradational contact with the underlying Wenlock Shale, it dominates the inter-reef sequence and encloses lentils of facies B. Facies C and D, which are crinoid limestones, only occupy the upper 7 meters of the 29 meters Wenlock Limestone sequence. Reefs occur most commonly between 3 and 10 meters from the top, e.g., in association with facies C and the upper part of A (Scoffin, 1971, p. 183). Bioherms are rare in the lower part of facies A and in facies D (Shergold and Bassett, 1970, p. 121).

Clay content and nodularity of the limestones increase down sequence in the inter-reef and distally in the off-reef. Off-reef facies occur southwest of Hilltop, and Scoffin (1971, p. 182–183) recognizes two main types:

E. thin-bedded fine bioclastic grainstones adjacent to the termination of major reef development near Hilltop and Easthope;

F. thin-bedded limestone-shale alternations, in which the limestones are argillaceous wackestone-mudstones, in the more distal off-reef.

Shergold and Bassett (1970, p. 118–119) subdivide facies F into lower "tabular limestone" and upper "nodular limestone" units (Fig. 9). There is a thin but extensive basinward progradation of facies D (Scoffin, 1971, p. 183) which Shergold and Bassett (1970, p. 119–120) name "crinoidal limestone" at the top of the sequence southwest of Hilltop. Above facies D there is a relatively rapid transition to green-brown siltstones of the Elton Beds.

There are numerous quarry exposures of the upper half of the limestone and the enclosed bioherms along the northeastern part of Wenlock Edge and its extension as Benthall Edge. The most important of these are shown in Figure 7. The disused quarry faces tend to be dirty and those of the working quarries change rapidly, so it is difficult to provide locality details of clean faces which will remain unchanged. Lea, Coates and Shadwell are large working quarries and Lilleshall is one of the largest disused quarries. Facies D, the "gingerbread" bioclastic gravels overlying the reefs, are well seen at Coates Quarry and Blakeway Hollow. The underlying Wenlock Shales (Coalbrookdale Formation) are well exposed in road cuts at Harley Hill, 1.5 kilometers north-northwest of Much Wenlock on the Shrewsbury Road, and the overlying Elton Beds are seen at Shadwell and Stretton Westwood Quarries (see Shergold and Bassett, 1970, fig. 14). The bioherms are described in detail by Scoffin (1971) and much of the following information is drawn from his work.

The biohermal limestone is a tabulate coral-stromatoporoid-algal dense to frame structure with bryozoans, crinoid fragments, and occasion-

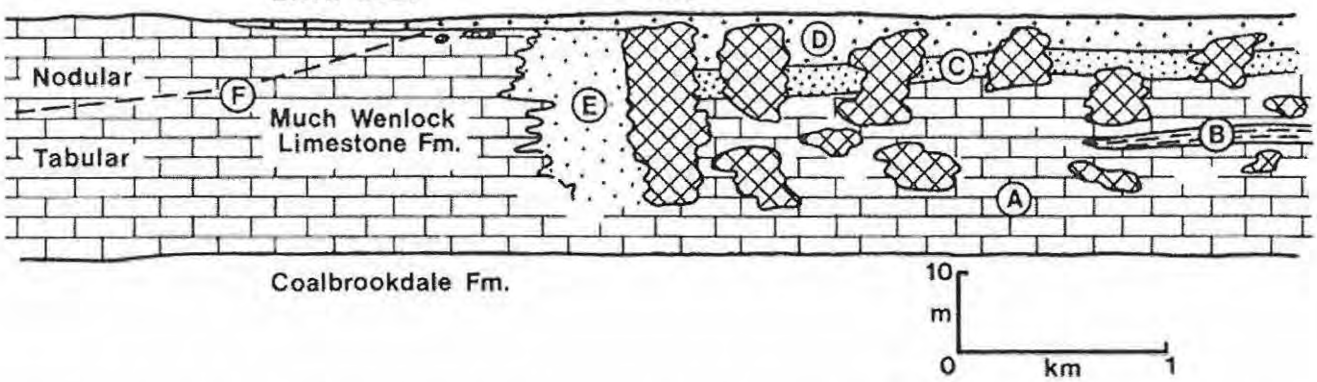

FIG. 9.—Lithofacies in the Much Wenlock Limestone Formation (Wenlock Limestone) around Hilltop on Wenlock Edge, England. A. crinoid biomicrite ("bluestone"); B. biomicrite ("Jack's Soap"); C. crinoid biomicrite ("measures"); D. crinoid biosparite ("gingerbread"); E. biosparite; F. fossiliferous micrite. Bioherms are cross-hatched; after Scoffin (1971, fig. 2) and Shergold and Bassett (1970, p. 119–120).

FIG. 10.—Bioherm margin, showing interfingering contact with bedded limestone at Coates Quarry, Wenlock Edge; hammer is 28 centimeters long.

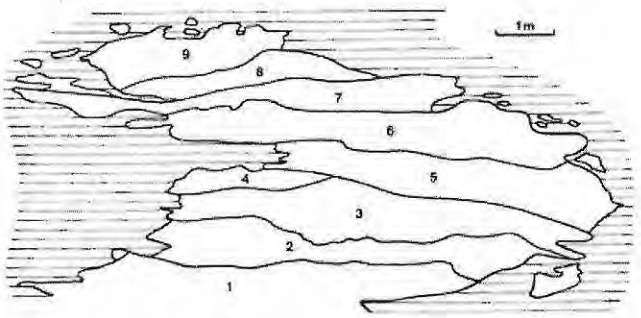

FIG. 11.—Cross-sectional plan of an Axelsro type bioherm at Coates Quarry, Wenlock Edge, showing growth stages marked by clay seams; from Abbott (1976, fig. 6), also see Scoffin (1971, fig. 17).

al pockets of brachiopods and bivalves. It forms highly irregular lensoid shapes in vertical sections, with numerous lateral outgrowths and invaginations (Fig. 10). The bioherms average 12 meters across and 4.5 meters thick and are largest at Hilltop where they reach 100 meters wide and 20 meters thick (Scoffin, 1971, p. 183). The distribution of reefs vertically and laterally shows no clear pattern, other than an increase upwards in the sequence and southwest towards Hilltop, but Scoffin (1971, p. 183–186, fig. 8a) notes a preferred northeast-southwest extension of growth.

Many of the bioherms rest upon basal lenses of coarse skeletal debris consisting of crinoids, bryozoans, brachiopods and corals (Scoffin, 1971, p. 188–189) which forms a well washed grainstone (Abbott, 1976, p. 2120). Once reef development was established growth appears to have been upward and outward from numerous loci, resulting in a succession of irregular overlapping lenses which are often separated by thin layers of green micrite and grey shale (Fig. 11). This coarse and irregular nodularity led to the term "ballstone" and is a characteristic feature of the internal structure of the reefs, referred to by Crosfield and Johnston (1914, p. 199): "the *ballstone* masses are generally ovoid and lenticular, and these are themselves most frequently composed of smaller, lenticular or phacoidal masses, which fit closely together."

Clay sedimentation appears to have profoundly influenced reef development and noticeably affects the lateral profile of bioherms: "generally indentations in the margins of the reefs correlate with clay-rich zones in the adjacent stratified limestone. This is most obvious in the case of bentonites" (Scoffin, 1971, p. 190). This control of reef growth by the rate of fine sediment deposition also extends to the formation of internal subdivisions within them; veneers of shale and micrite locally extinguish growth within a reef and provide new surfaces for lateral colonization. In this way the lenticular "ballstone" structure was built up by loose sediment interfering with organic growth. The resulting clay seams have been used as time planes to reconstruct the sequence of bioherm development (Scoffin, 1971, p. 196; Abbott, 1976, p. 2122).

Contacts with inter-reef facies are sharp and occasional talus wedges of coarse debris extend outwards from the reefs. Rarely crinoid beds are also found thinning away from reefs. The upper surfaces of bioherms are normally convex and their relief appears to have been relatively low, ranging from 0.5 meter in reefs 5 meters across to a maximum of 3 meters in the largest reefs. "The growth surface was horizontal to slightly convex, with irregular hollows, and sloped at a gentle angle (about 15 degrees) down to the reef margins which had low reliefs and were regularly swamped by loose sediment" (Scoffin, 1971, p. 216).

Tabulate corals dominate the reefs, forming 10–20 percent of the volume (Scoffin, 1971, p. 198–202); and Abbott (1976, p. 2120) describes a vertical succession within individual bioherms from *Halysites*, through *Heliolites* and *Favosites* to stromatoporoid dominated communities reflecting a gradual increase in water movement. The principal stromatoporoids in the bioherms are domical *Actinostroma* and *Stromatopora*, and laminar *Stromatopora* and *Labechia*. Bryozoans (*Hallopora*, *Rhombopora*, *Fistulipora*, and *Fenestella*) are also abundant and rugose corals (*Entelophyllum*) are common. Laminar tabulates (*Alveolites* and *Thecia*) are also present. Non-skeletal stromatolites, occasionally associated with the problematic micro-organisms *Rothpletzella* and *Wetheredella*, occur as irregular crusts a few millimeters to a few centimeters thick lining reef cavities and veneering skeletons and sediment. Associated organisms are crinoids, brachiopods, ostracodes, foraminifers, gastropods and trilobites.

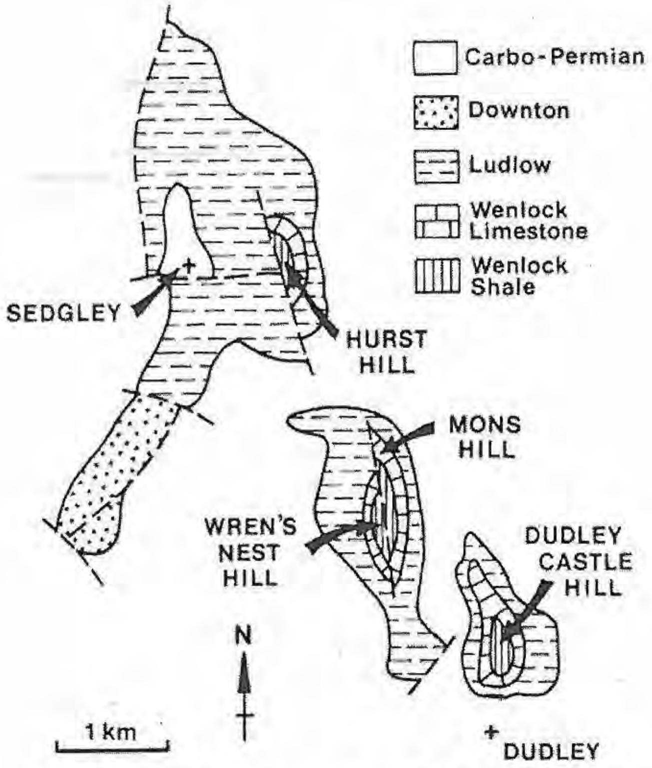

FIG. 12.—Silurian outcrops near Dudley, England.

The principal organisms: non-laminar tabulates, stromatoporoids, rugosans and bryozoans form an intricate irregular framework in which most upper surfaces are encrusted by stromatolites while bryozoans commonly encrust undersurfaces. A large proportion of original cavity space was largely filled by biomicritic matrix penecontemporaneously with the growth of organisms (Scoffin, 1971, p. 209–210), indicating that the reef organisms had to cope with more or less continuous fine sediment deposition. Skeletal grainstones were unable to filter down into the dense frames and are localized in pockets and lenses in the reefs, probably representing open hollows in the reef surface (Scoffin, 1971, p. 209). The upper parts of cavities unfilled by biomicrite often show a layer of fine micrite, representing a late stage of internal sedimentation, followed by a final sparry calcite cement plug. Original cavities which were subsequently completely filled by particulate sediment as reef development proceeded can be recognized from downward growing encrusting organisms, such as *Fistulipora* bryozoans, beneath framework masses (Scoffin, 1972, fig. 2b). Most of the residual cavity which was ultimately sparite-filled is associated with *Halysites* palisades (Scoffin, 1972, p. 568; Abbott, 1976, p. 2123), but there are also some intra-skeletal voids.

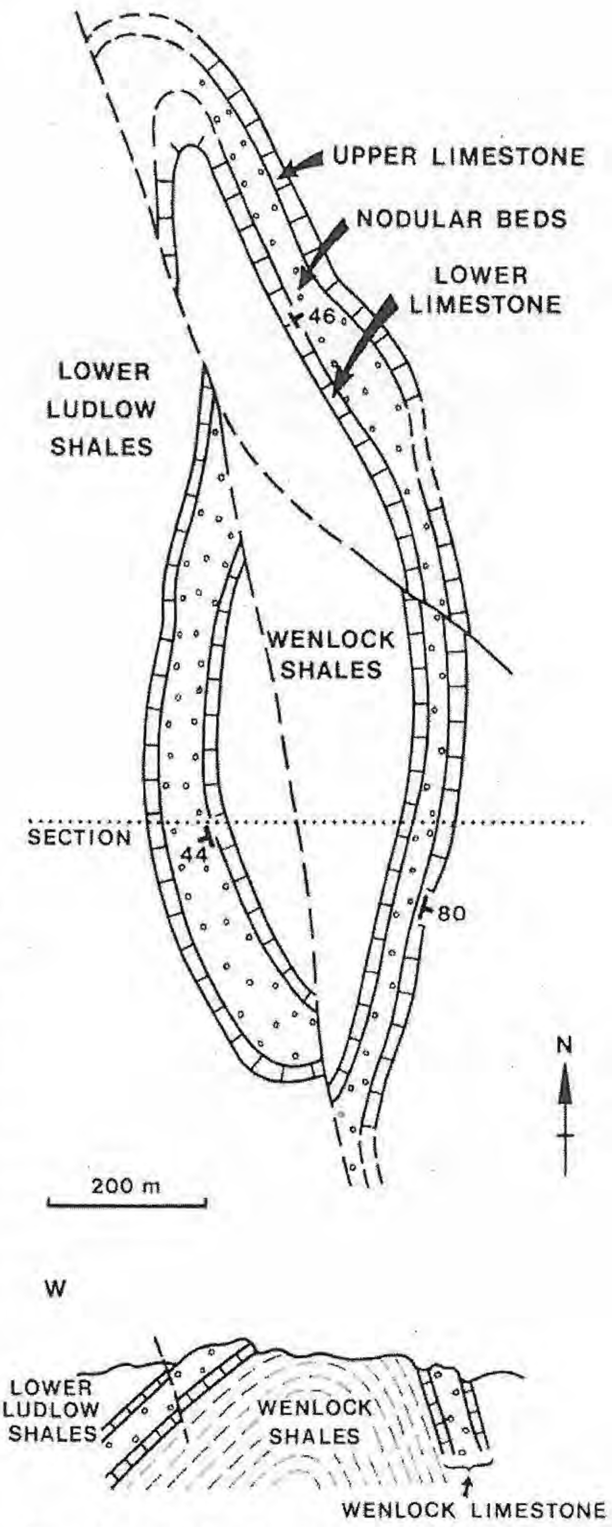

FIG. 13.—Map and section of Wren's Nest Hill pericline near Dudley, England (from Butler, 1939, pl. 3; Hamblin *et al.*, 1978, fig. 1).

The inherent weakness of these reefs is reflected by post-burial compaction features including: "rotation of the solid masses, the fracturing of skeletons, the squeezing and splitting of micrite and the injection of clay minerals through new openings in the reef" (Scoffin, 1971, p. 203; also see Abbott, 1976, fig. 7). These enhance the original lenticular components of the reefs as Crosfield and Johnston (1914, p. 223) realized, although they attributed the movements to earth movements rather than differential compaction. Secondary porosity was also produced, on a limited scale, by preferential dissolution of bryozoan and coral skeletons usually on the ceilings of original growth cavities (Scoffin, 1972, p. 575).

Crosfield and Johnston (1914, p. 221) concluded that the reefs at Wenlock Edge grew in shallow but relatively quiet water, an interpretation supported by Scoffin (1971, p. 216) who also recognized evidence for extreme shallowing which ultimately terminated reef growth in the area.

Dudley.—Wenlock Limestone with reefs outcrops in three en echelon periclinal inliers between Dudley and Sedgley, 14 kilometers west-northwest of Birmingham (Fig. 12). These form small, but locally prominent, hills: Dudley Castle Hill, Wren's Nest Hill, with Mons Hill just to the north, and Hurst Hill. Intensive mining has created underground caverns at Castle Hill and the Wren's Nest, but these are now in a state of collapse. The area is famous for well preserved fossils from the limestone, especially trilobites such as *Calymene blumenbachi*, the "Dudley Locust."

No specific studies of the reefs have been made here, but the stratigraphy of the limestone is described by Butler (1939), and general details of the local geology are to be found in Murchison (1839, p. 483–487), Jukes (1859), Whitehead and Eastwood (1927), and Whitehead and Pocock (1947).

The Wenlock Limestone is approximately 60 meters thick and includes two relatively pure limestone units, the Lower and Upper Quarried Limestone, separated by shales and nodular limestones termed the Nodular Beds. Butler (1939) recognized the following units:

lower Ludlow Shale	
	5. Passage Beds (1.3 m), nodular limestones and shales;
	4. Upper Quarried Limestone (7.3 m), bedded bioclastic and stromatoporoid limestone;
Wenlock Limestone	3. Nodular Beds (31.0 m), shales with nodular and thin bioclastic limestones;
	2. Lower Quarried Limestone (12.8), bedded bioclastic stromatoporoid limestone;
	1. Basement Beds (3.4 m), bioclastic limestones and shales.
Wenlock Shales	

At Dudley the areas of more massive and purer limestone were termed "crog-balls" by quarrymen. These occur most commonly in the Nodular Beds where they are generally 3–6 meters wide and 1.5–3 meters high and are reef masses dominated by tabulates, stromatoporoids, rugose corals and bryozoans with pockets rich in brachiopods (Butler, 1939, p. 448). "Crog-balls" also occur in the Lower and Upper Quarried Limestones but they are fewer and flatter and contain mainly crinoid fragments, tabulates, and bryozoans (*Coenites*), with no large rugosans or stromatoporoids. In a comparison between the Wenlock Edge "ballstones" and the Dudley "crog-balls" Croffield and Johnston (1914, p. 210–211) concluded that the Dudley "crogs" were not similar to Wenlock Edge "ballstone." However, they were comparing "ballstone" with "crog" material from the Lower Quarried Limestone. From Butler's description it seems clear that the "crog-balls" of the Nodular Beds are reefs comparable with those of Wenlock Edge, but that the "crog-balls" of the Quarried Limestones are flatter lenses of coarse bioclastic debris.

The best exposures at present are at Wren's Nest Hill which is now a nature reserve (Hamblin *et al.*, 1978). The periclinal fold which brings up the Wenlock Limestone is asymmetric, dipping westwards at 50 degrees and eastwards at 70 degrees (Fig. 13). The Lower and Upper Quarried Limestones have been removed in deep trenches on the east side of the hill, and in a complex series of caverns on the west side where an underground canal was used to ship out the rock.

Other Localities.—Bioherms are known in the Wenlock Limestone from Walsall, Abberley and Malvern (Mitchell *et al.*, 1961; Phipps and Reeve, 1967), Woolhope (Squirrell and Tucker, 1960), May Hill (Lawson, 1955), and Usk (Walmsley, 1959) (Fig. 5). At present, exposures at these areas are relatively poor and there has not been much specific emphasis of the bioherms except by Penn (1971) at Malvern.

Oslo Region

Bioherms and biostromes are widely distributed at several levels in the Llandovery and Wenlock rocks of the Oslo Region (Kiaer, 1908) but have not yet been described in detail. They occur within a variable sequence of marine sediments (Bjørlykke, 1974, p. 24–31) which is influenced by influx of siliciclastic detritus from the north and northwest (Størmer, 1967, p. 204–207) reflecting the proximity of the Caledonian mobile belt. Marine transgression over this shelf area during the lower and middle Llandovery was followed by progradation of sand from the north during the upper Llandovery. Carbonate deposition, including reef development, was established three times, in the late Llandovery, lower Wenlock and middle Wenlock, and alternates with shale-mud-

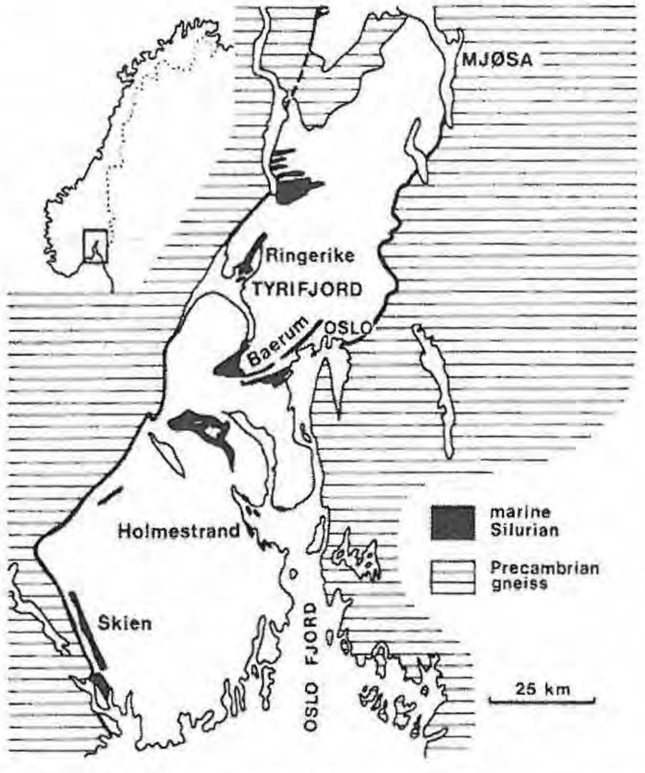

FIG. 14.—Distribution of marine Silurian sediments in the Oslo Region. Other rocks in the Oslo Graben are undifferentiated. Localities with reefs are named; from Dons and Larsen (1978, pl. 1). Details of the Ringerike area are shown in Figure 16.

stone-sandstone sedimentation (Fig. 4). Marine deposition during the Llandovery and Wenlock resulted in the formation of 600 meters of rock and was terminated in the late Wenlock by the onset of continental Old Red Sandstone-type conditions.

The Oslo Region was folded fairly intensively during the Caledonian Orogeny but the main character of the area was created by intracratonic rifting associated with volcanicity and subsidence during the Lower Permian (Dons and Larsen, 1978). The result is that Lower Paleozoic sedimentary rocks are now preferentially preserved within the Oslo Graben where they are associated with a diverse suite of intrusive and extrusive Late Paleozoic rocks which cover more than 75 percent of the downfaulted area. The graben extends north-northeast from Oslo to Lake Mjøsa where it joins the Caledonian nappe area, and south-southeast into the Skagerrak extension of the North Sea (Fig. 14). This area is 200 kilometers long and 35–65 kilometers wide and is bounded on the west and east by Precambrian gneisses. Further information on the geology of the region is provided by Holtedahl (1960), Henningsmoen and Spjeldnaes (1960), and Seilacher and Meischner (1964). The Steinsfjord area of Ringerike, where good examples of the reefs occur, is described by Whitacker (1977).

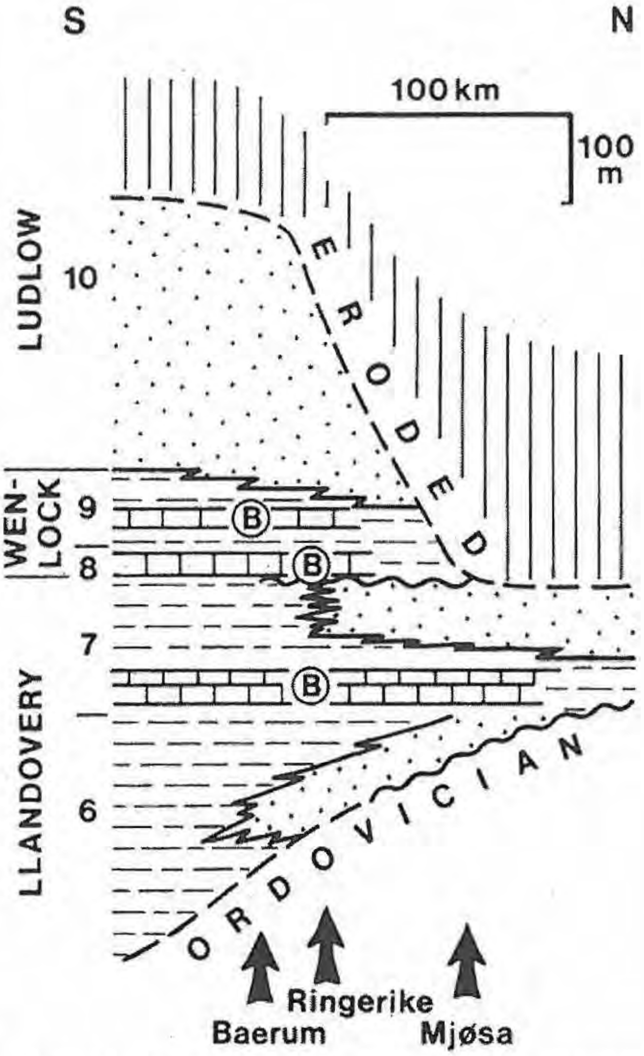

FIG. 15.—Position of bioherms and biostromes (B) in the broad sedimentary facies context of the Silurian of the northern Oslo region; scales very approximate, adapted from Bjørlykke (1974, figs. 11 and 12).

A particular problem of the Oslo Silurian succession concerns lithostratigraphy and correlation. Kjerulf (1855), followed by Kiaer (1908) divided the local Cambro-Silurian sequence into ten units, termed stages. These were changed into series by Strand and Henningsmoen (1960). However, they do not correspond with either formal stages or series; instead they combine both lithostratigraphic and biostratigraphic characters and they exhibit diachronism and time equivalence (Bassett and Rickards, 1974). Broadly, "Stages" 6 and 7 represent the Llandovery, 8 and 9 the Wenlock, and 10 the Ludlow (Fig. 15). These have been applied to the whole area and have provided a convenient interim nomenclatural scheme, but they require revision. A new lithostratigraphical scheme with revised correlations is in preparation.

Silurian rocks with bioherms and biostromes outcrop in patches, usually no more than 15 kilometers across, from Ringerike in the north

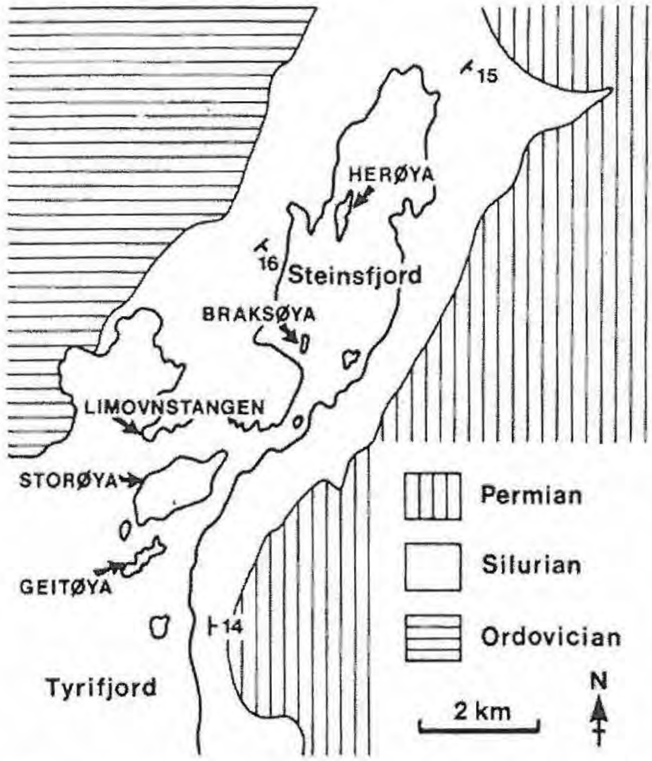

FIG. 16.—Localities, Ringerike district, Norway (after Whitacker, 1977, fig. 1).

FIG. 17.—Upper Llandovery stromatoporoid and tabulate coral dominated bioherm enclosed by bedded bioclastic limestone, Limovnstangen, Ringerike, Norway.

through Baerum, and Holmestrand to Skien in the south (Fig. 14). The following descriptions are based upon Kiaer (1908), with details from Hanken *et al.* (1978) which utilize a few of my own observations in Tyrifjord. I am indebted to Nils Martin Hanken, Snorre Olaüssen, and David Worsley for making information, on which most of this account depends, available from their work in progress.

Bioherms and biostromes occur at three general horizons in the Llandovery and Wenlock (Fig. 15):

1. upper Llandovery bioherms at Ringerike;
2. lower Wenlock bioherms at Ringerike and Skien;
3a. mid-Wenlock bioherms at Holmestrand and Skien;
 b. late Wenlock biostromes at Ringerike, Baerum, Holmestrand and Skien.

These areas were all in marginal marine situations during much of this time but at present it is difficult to place them more precisely in their environmental setting.

Llandovery.—Fronian (lower upper Llandovery) bioherms occur in Stage 7b at Ringerike and Baerum. They are small lensoid masses up to 6 meters across and 2 meters high dominated by halysitids and stromatoporoids with minor favositids, heliolitids and syringoporids. *Girvanella* and bryozoans may have had a binding effect. The matrix is microspar after micrite, with numerous brachiopods, and rare bumastid trilobites, gastropods and cephalopods. They grow on biosparite banks composed of pentamerid and crinoid debris, and laterally show near-vertical inter-fingering contacts with well-bedded crinoid biosparites. The upper surfaces and overlying sediments suggest that growth stopped at a stage of further diversification as a result of a transgressive episode.

A good example of these bioherms occurs at the base of Stage 7b on Limovnstangen, a peninsula jutting south into Tyrifjord (Fig. 16). It contains laminar and domical stromatoporoids up to 50 cm across with favositids and abundant *Halysites*. There are sharp lateral contacts with bedded bioclastic limestone (Fig. 17).

Lower Wenlock.—Sheinwoodian (lower Wenlock) bioherms occur in Stage 8c at Ringerike, particularly on the islands in Steinsfjord and northeastern Tyrifjord. Kiaer (1908, p. 79–82, figs. 19 and 20) describes them at Geitøya and Braksøya (Fig. 16) and also draws attention to a horizon of large stromatoporoids a few meters

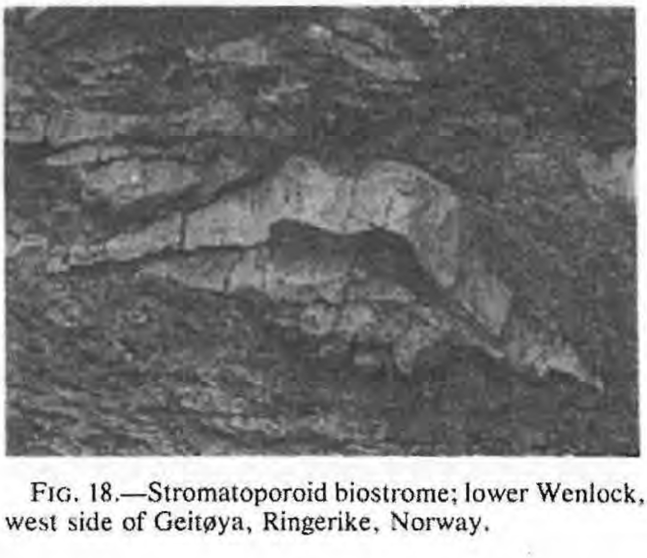

FIG. 18.—Stromatoporoid biostrome; lower Wenlock, west side of Geitøya, Ringerike, Norway.

higher in the sequence (p. 89, fig. 19). The bioherms are irregularly dispersed through a 20 meters thick sequence. Individual structures have maximum diameters of 15 meters and heights of 8 meters, but there are also some very small bodies. Mound-structure appears to be dominated by encrusting *Girvanella*, *Rothpletzella*, *Wetheredella* and *Halysis*, with subordinate halysitids. Diversity is low and a few brachiopod species are the only other organisms observed. Radial growth appears to have taken place from several loci, and the primary relief was probably low (?0.5 meter). The upper surfaces are irregularly convex and the flanks interfinger with bedded limestones. Inter-reef beds contain a varied fauna of brachiopods (*Dicoelosia*, *Skenidioides*, atrypids and rhynchonellids), large solitary corals (*Phaulactis*), and stromatoporoids. Evaporite pseudomorphs occur within the bioherms and desiccation cracks occur in the beds immediately overlying them.

On the west side of the island of Geitøya in Tyrifjord (Fig. 16) the bioherms are flat-based coalescive mounds up to 5 meters thick overlying calcareous siltstones. They have irregular upper surfaces and are separated from the overlying stromatoporoid horizon by a few meters of argillaceous limestone. The stromatoporoid bed is a 2-meters thick biostrome of laminar and domical forms up to 80 centimeters across (Fig. 18).

Middle-late Wenlock.—Biostromes and bioherms of medial Wenlock age are developed in the middle parts of the Steinsfjord Formation (Worsley, per. comm., 1979) (Stage 9c) of Holmestrand and Skien. In Holmestrand, biostromes are laterally persistent units 1–4 meters thick, composed of tabulates (favositids, heliolitids, "*Thecia*" sp. and syringoporids), rugose corals, algae, bryozoans (*Coenites* sp.), stromatoporoids, brachiopods, molluscs and ostracodes. Corals occur both in place and moved (see Kiaer, 1908, fig. 57). Kiaer noted these biostromal units at three horizons, which he termed Korallenhorizonten I, II, and III.

Small bioherms occur locally in the lower part of Korallenhorizont II and approximately 20–30 meters above Korallenhorizont III. The lower bioherms are 2–3 meters in diameter and less than 0.5 meter high with relatively flat bases and tops. Laterally they interfinger with bedded bryozoan fragment limestones in which *Girvanella* and red algae encrust the clasts. They are dominated by the tabulate "*Thecia*" which grows in thin layers with marginal tongues and sediment inclusions. The rugosan *Acervularia* is occasionally present.

The upper bioherms occur in a sequence with high faunal diversity. Kiaer (1908) identified approximately 80 species, not counting algae, *Problematica* and trace fossils. The bioherms are generally only 0.5–0.9 meter wide and 0.4–0.7 meter high, but one much larger structure 25 meters across and several meters high also occurs. The framework consists of stromatoporoids, tabulates ("*Thecia*" and favositids), and colonial rugose corals. Bryozoans, such as *Coenites*, may have functioned as binders. The matrix includes both micrite and sparite. Crinoid debris fills small channels in the single large bioherm seen.

Biostromes of late Wenlock age occur in the upper part of the Steinsfjord Formation (Stage 9f) in the Ringerike, Baerum, Holmestrand and Skien districts (Fig. 14), a distance of 150 kilometers. In all exposures they occur approximately 30 meters below the junction with the overlying red and grey sandstones of the Ringerike Group. Despite their wide lateral extent they are only 1 meter thick. Their persistence is probably a result of a minor regional transgressive episode. In Baerum, near Oslo, the biostromes show slight local topography and are almost biohermal in character. Kiaer (1908) reports small stromatoporoids, *Favosites* and *Monticulipora* as major biostrome components at good exposures on the western side of Herøya in Steinsfjord, Ringerike (Fig. 16). *Amplexopora* also occurs, with brachiopods, cephalopods, gastropods, rugose corals, and *Girvanella* oncolites, but the overwhelming dominance of favositids gives the biostrome biota a restricted aspect. It represents the final accumulation of stenohaline marine organisms prior to the encroachment of non-marine red beds into the region.

Gotland

The reefs of Gotland are widely known through the publications of Wiman (1897), Hadding (1950), Jux (1957), and Manten (1962 and 1971). The geological succession of the island is famous and Gotland, rather than the Silures, almost gave its name to the system. The sequence is relatively thin, approximately 450 meters, but the dip is very low and the entire island, 140 kilometers long (including Fårö in the northeast) and 50 kilometers wide, exposes only Silurian rocks which range from upper Llandovery to upper Ludlow. Although the succession includes discontinuities it is relatively complete.

Bioherms or biostromes occur at nearly all levels in the sequence and their distribution, stratigraphic setting, size and morphology are well documented, mainly through Hede's (1925a and b, 1927a and b, 1928, 1929, 1933, 1936, 1940) careful mapping of the geology, and Manten's (1971) extensive examination of them. In contrast the internal structure, paleoecology and sedimentology of the reefs remain only very generally understood.

Gotland is situated in the central Baltic (Fig. 1) on the cratonic Russian Platform. To the west, on

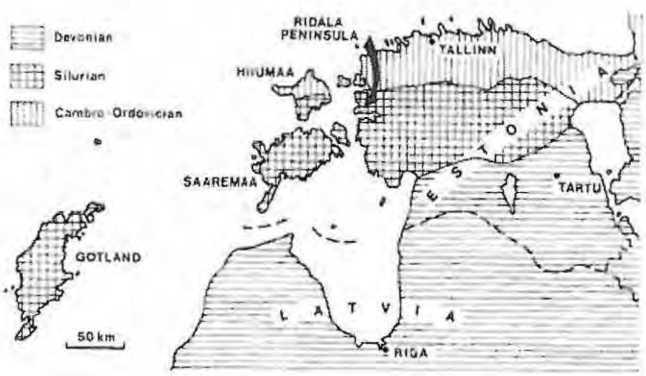

FIG. 19.—Silurian outcrop and localities, Estonia.

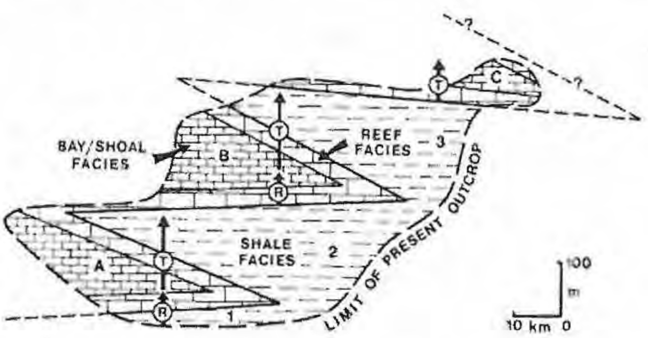

FIG. 20.—Idealized and partially hypothetical diagram of carbonate/shale wedge configuration within the Gotland sequence showing the position of the main reef facies and the alternately shallowing-up/regressive (R) and deepening-up/transgressive (T) nature of the succession. Wedges A (Högklint-Slite), B (Halla-Klinteberg-Hemse), and C (Burgsvik-Hamra-Sundre) are mainly carbonate, with reef facies preferentially developed distally and algal, oolite, bioclastic bay/shoal facies proximally. Wedges 1 (Visby), 2 (Slite-Mulde), and 3 (Hemse-Eke) are essentially shale and argillaceous limestone.

the Swedish mainland, erosion has largely removed Lower Paleozoic sediments, and the Precambrian metamorphic basement is exposed over much of the region forming the Baltic Shield (Størmer, 1967). In Scania, at the southern tip of Sweden, a relatively thick, shale-dominated Silurian succession occurs (Regnéll, 1960, p. 25–31) in the Oslo-Scania-Baltic Syneclise (trough) (Størmer, 1967, fig. 22). In contrast the limestone-shale succession of Gotland formed on a shallower shelf area and has much more in common with the Estonian sequence which is a continuation of the Gotland outcrop northeastwards on the eastern side of the Baltic (Fig. 19).

The Baltic area north of the syneclise is characterized by a thin (less than 1 kilometer) Lower and Middle Paleozoic sedimentary sequence resting unconformably on Precambrian crystalline basement, and boreholes have proved uppermost Precambrian, Cambrian, and Ordovician sediments beneath Gotland. The Caledonide mobile belt was several hundred kilometers to the west and the Baltic sequence is flat-lying and undeformed. Manten (1971, p. 7–32) further summarizes the regional setting of Gotland.

The near horizontality of the beds on Gotland, combined with the rare observation of graptolites in these facies, has presented stratigraphic problems which persist to the present day. The stratigraphic units erected by Hede which are still in use show marked diachronism in the upper part of the succession (Martinsson, 1967; Michael Bassett, pers. comm., 1979). Yet Murchison (1847) quickly recognized the main feature of the Gotland sequence: a series of rock units dipping at a very low angle to the southeast with the oldest strata exposed along the northwestern coastline. The astuteness of this observation is confirmed by the subsequent mistakes made by Lindström (1884) who was misled by the low inclination of the beds (the regional dip is only a fraction of one degree to the southeast) into believing that one series of rocks could be traced all over the island and that *lateral* facies variation alone accounted for lithological changes. The unlikelihood of this interpretation was becoming clear by the end of the nineteenth century (see Moberg, 1910, p. 40–57) but variants of it continued to be developed (Wedekind and Tripp, 1930) and repeated by workers up to and including Jux (1957) (see Manten, 1971, p. 32–42).

The Gotland sequence is dominated by limestones and shales. Coarser siliciclastic sediments occur at only two horizons, in the Slite Siltstone and the Burgsvik Sandstone, which together represent no more than 10 percent of the total succession (Fig. 3). The limestones, which include a diverse array of bioclastic, reefal, oolitic, oncolitic and argillaceous carbonates, occur as two distinct wedges narrowing to the south overlain by shale wedges narrowing to the north. The top of another shale unit occurs at the base of the exposed succession, and the base of a third limestone unit occurs in the south of the island (Fig. 20). The sequence is relatively thin and disconformities occur at several levels, particularly within the limestone wedges. Those affecting reefs are especially prominent at the top of the Högklint Beds and planing the top of reefs at Kuppen and Holmhällar (see below).

The broad depositional trend throughout the Silurian was shallowing from the north due to influx of fine siliciclastic detritus and the formation of extensive carbonate sediments (Laufeld, 1974a, p. 7). This southern progradation was complicated by transgressive-regressive cycles which produced the pattern of interfingering wedges of shelf carbonates to the north and relatively deeper water shales to the south. By Ludlow time there

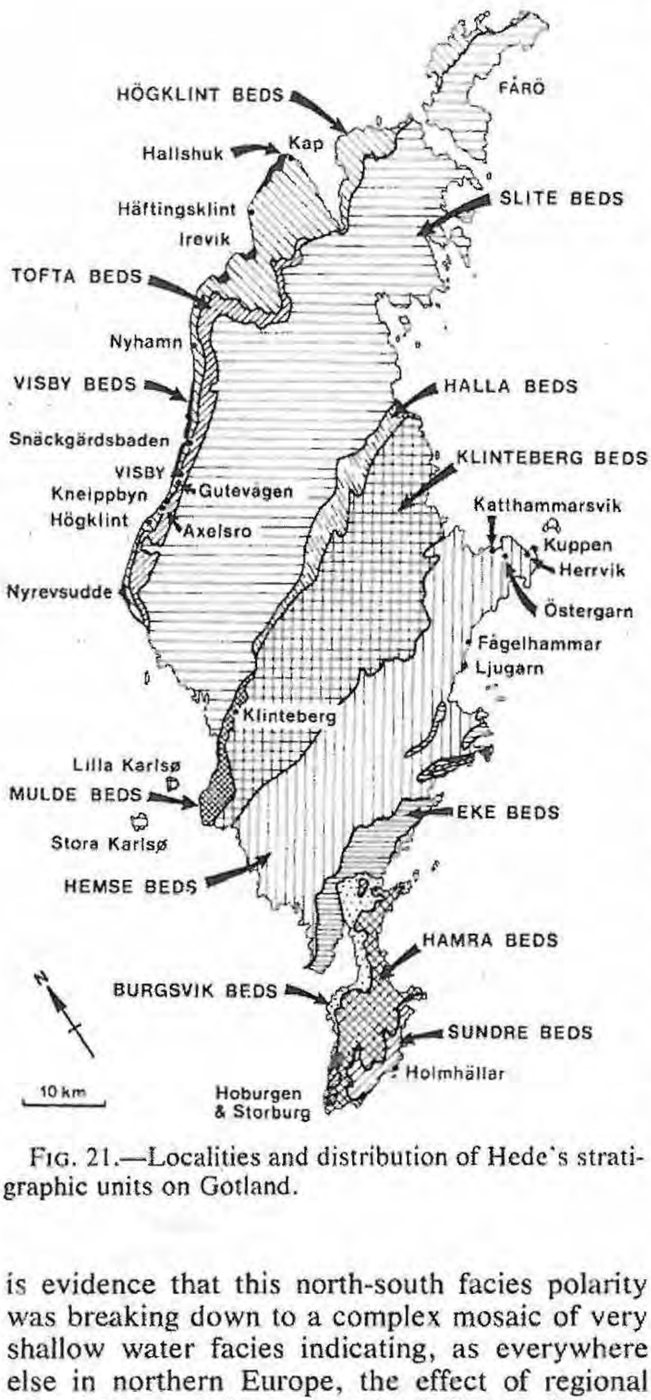

FIG. 21.—Localities and distribution of Hede's stratigraphic units on Gotland.

is evidence that this north-south facies polarity was breaking down to a complex mosaic of very shallow water facies indicating, as everywhere else in northern Europe, the effect of regional regression and the approach of Old Red Sandstone continental sedimentation.

The current stratigraphy is based upon the work of Ernhold Hede who, together with other colleagues, prepared 1:50,000 geologic maps with accompanying memoirs of the whole island. He recognized 13 major stratigraphic units (Fig. 21, Table 1) which are summarized by Hede (1960, p. 44–52) and Laufeld (1974a, p. 7–13). These are topostratigraphic units which combine aspects of both litho- and biostratigraphic units. Consequently, there is not always a correlation between Hede's units and the major lithofacies (Figs. 21 and 22). This is particularly so for the Slite, Klinteberg and Hemse Beds which are all essentially limestones in the northeastern parts of their outcrops, but pass laterally into shales towards the southwest. Hede's major units are divided into sub-units distinguished either by name or letter (Manten, 1971, p. 277–422; Laufeld, 1974a, p. 7–13). Biostratigraphic correlation with standard European divisions has been made relatively recently by Martinsson (1967) with slight modification by Bassett and Cocks (1974).

Hede (1960) provides a useful guide to Gotland geology and detailed work is greatly helped by Laufeld's (1974b) comprehensive inventory of localities. Manten (1971) describes and illustrates numerous reef outcrops. Stromatoporoids, which are the dominant reef building organisms, have been described by Mori (1968, 1970) and stromatoporoid morphotypes are discussed by Kershaw and Riding (1978). Stel (1978a) describes tabulates, especially favositids, from the Gotland succession. Calcareous algae are described by Rothpletz (1913) and Hadding (1959). Gotland rugosans are described by Wedekind (1927), and Brood (1976) outlines bryozoan paleoecology. Other publications on the paleontology of Gotland are listed by Manten (1971, p. 423–424). The faunal and floral succession through a section of the Visby, Högklint and Tofta Beds near Visby is being documented in detail by a group of specialists.

Murchison, having learned from his original mistaken conception of the Wenlock Edge bioherms as concretions, recognized the reefal character of the Gotland deposits (1847). Studies of the reef limestones were subsequently made by Wiman (1897) and Hedström (1910) near Visby, and by Munthe (1910) in southern Gotland. Both Hadding (1941, p. 79–94) and Manten (1971, p. 56) review work on Gotland reefs. Crosfield and Johnston (1914, p. 212–214) noted the similarity between Wenlock Edge "ballstone" and Gotland reef rock but commented "the longer continuance in time of the reef phase in Gotland . . . has introduced a greater variety into the fauna of the reefs, and also into the lithology and faunas of the associated beds, both at the base of and surrounding the reefs" (p. 214).

Hadding's work (1941 and 1950) represents an important step forward in understanding Gotland reefs. He used thin sections to study the petrography and he plotted out the reef outcrops from Hede's maps to clarify their distribution. Rutten (1958) also surveys the spectrum of reef occurrences on Gotland.

The broad pattern of carbonate and shale wedges which makes up the Gotland sequence was recognized by Wedekind and Tripp (1930), and further emphasized by Jux (1957). Jux's attempts at a general facies analysis of the succes-

TABLE 1.—HEDE'S (1960) STRATIGRAPHIC UNITS FOR GOTLAND WITH APPROXIMATE AGES (AFTER BASSETT AND COCKS, 1974, FIG. 1), MAXIMUM THICKNESSES AND PRINCIPAL LITHOTYPES (AFTER LAUFELD, 1974A)

LUDLOW	Sundre Limestone	10 m+	bioclastic limestone, biostromes
	Hamra Group	40 m	argillaceous & bioclastic limestone, bioherms
	Burgsvik Group	47 m	oolitic limestone, sandstone, bioherms
	Eke Group	15 m	shale, argillaceous & bioclastic limestone, bioherms
	Hemse Group	100 m	bioclastic & argillaceous limestone, shale, biostromes & bioherms
WENLOCK	Klinteberg Group	64 m	argillaceous & bioclastic limestone, shale, bioherms
	Halla Group/Mulde Marl	20 m	argillaceous & oolitic limestone, shale, bioherms
	Slite Group	100 m	bioclastic & argillaceous limestone, shale, bioherms
	Tofta Limestone	8 m	argillaceous limestone
	Högklint Group	35 m	bioclastic limestones, bioherms
	Upper Visby Marl	16 m	argillaceous limestone, shale, bioherms
LLANDOVERY	Lower Visby Marl	9 m+	shale, argillaceous limestone

sion have been strongly criticized by Manten (1971, p. 39–42) as being idealized and simplistic. Nevertheless, the gross features which Jux stressed do dominate the sequence and his approach should be a stimulus to further refinement of facies patterns within the succession.

Manten (1962 and 1971) made a major contribution by his detailed documentation of the form and distribution of Gotland reefs. He placed little emphasis on sedimentologic or paleoecologic analysis, but he was nevertheless able to recognize three main reef types which he named Upper Visby, Hoburgen and Holmhällar (1971, p. 56–58). In addition, he recognized Stäurnaser and Fanterna types on Stora Karlsø Island off the southwest coast (1971, p. 243). The principal features of the three main reef types, as defined by Manten, are as follows:

Upper Visby.—Lensoid to conical reefs with a very marly matrix enclosed by marlstone and argillaceous limestone; typically less than 10 m^2 in section and with a height:length ratio of between 1:1 and 1:5; dominated by corals and rather laminar stromatoporoids, both of which are relatively small, and lacking calcareous algae and reef detritus; species diversity is moderate and the organic composition is rather variable.

Hoburgen.—Very elongate lensoid to conical reefs with a marly matrix, enclosed by limestone and argillaceous limestone; typically about 100 m^2 in section and with a height:length ratio of between 1:1 and 1:50; dominated by lenticular stromatoporoids and corals, both of which are quite large, together with common calcareous algae; surrounded by crinoidal reef detritus; species diversity is high and the organic composition is generally variable.

Holmhällar.—Crescentic reefs with only a little included marl and enclosed by rather pure limestone; typically more than 1000 m^2 in section, with a height:length ratio of between 1:15 and 1:75; dominated by large round or irregular and high stromatoporoids with calcareous algae very common; surrounded by reef detritus; species diversity is low and the organic composition is rather uniform.

The Upper Visby type of reef mainly occurs in the Upper Visby Beds, near the base of the sequence along the northwest coast, but the Hoburgen type, which is the most common, is found in every unit except the Lower and Upper Visby Beds, the Tofta Beds and the Sundre Beds. The Holmhällar type is found in the Hemse, Hamra and Sundre Beds in the southern part of the island (Manten, 1971, p. 58). The Stäunasar and Fanter-

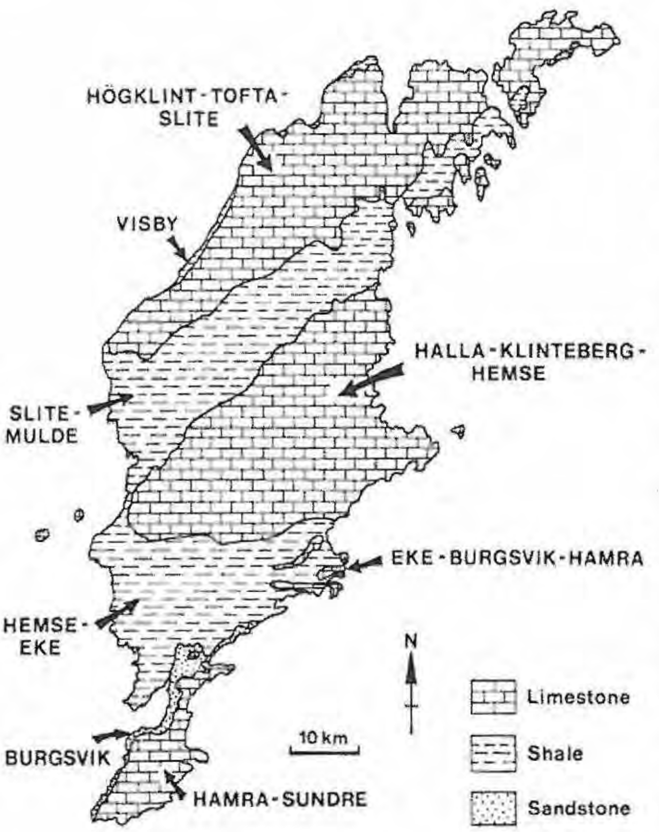

FIG. 22.—Lithofacies and their relation to Hede's stratigraphic units on Gotland, compare with Figure 20; from Eriksson and Laufeld (1978, fig. 1).

na reef types are restricted to Karlsø Island and are dominated by corals.

Manten's three main reef types are basically well founded, but they break down in the Hemse reefs of the Östergarn-Ljugarn area, where he admits that variants occur (Manten 1971, p. 357, 374 and 386). These have a greater variety of stromatoporoid morphotypes than either the Hoburgen or Holmhällar types, and a greater density of organisms than the Hoburgen type. They are here named the *Kuppen* type from the locality near Herrvik (Fig. 21). The name Upper Visby, suggested by Manten, is appropriate in the sense that these tabulate dominated structures are common in the Upper Visby Beds, but it also tends to imply a restriction to this unit whereas they also occur in the Lower Visby Beds and similar structures occur in the Klinteberg Beds at Klinteberg (Manten, 1971, fig. 165). In order to avoid direct association between reefs of this type and the Upper Visby Beds, and also to avoid confusion between stratigraphic units and reef types it is here proposed to use the name Axelsro reef type in place of Upper Visby reef type. Good examples occur in cliff sections near Axelsro, 5 kilometers southwest of Visby. Although the Axelsro reefs are mainly tabulate dominated, stromatoporoids also become important in the larger examples (Ted Nield, pers. comm., 1979). The Hoburgen, Kuppen and Holmhällar types are essentially stromatoporoid reefs. The Axelsro and Hoburgen reefs are bioherms but thin biostromal units are also associated with the Axelsro reefs. The Kuppen and Holmhällar reefs are biostromal so far as is known. Besides these broad compositional and geometric features the various reef types can be compared and contrasted in detailed composition and structure (Table 2). Details, and examples of them, are given below; localities follow Laufeld (1974b).

Axelsro Bioherms and Biostromes.—These reefs in argillaceous and bioclastic limestone are mainly small tabulate dominated bioherms which are closely comparable with the Wenlock Edge reefs. Generally they are dense, grading into loose, structures, although locally they are solid. The principal organisms are favositids, heliolitids, halysitids and laminar to low domical stromatoporoids all of which are usually less than 25 centimeters across, although they can be up to 50 centimeters across. There is no distinct boundary between very small examples of these reefs, such as a tabulate overgrown by a stromatoporoid and encrusted by a few bryozoans, and level bottom communities of isolated individuals.

Two Axelsro sub-types can be distinguished: mud-based, usually small structures up to 2 meters across; and larger, gravel-based structures up to 5 meters across (Fig. 23). The presence of gravel lenses beneath many of the larger examples suggests that the reef building organisms preferentially colonized coarse substrates when these were available. The other possible explanation, that the reef itself produced or localized gravel deposition, is weakened by the common occurrence of gravel bands without overlying reefs and the scarcity of gravel bands lateral to reefs. The gravel appears to occur in channels which represent the approach of crinoid shoals, the coarse sediment being swept in from higher energy environments, probably to the northwest.

The Axelsro type are well seen in the Upper Visby Beds along the northwest coast between Nyrevsudde and Hallshuk (Fig. 21). Small examples are well exposed at Halls Huk 3 where a series of them occur at the base of the cliff in the Upper Visby Beds about 10 meters below the base of the Högklint. At this horizon several small structures occur within a lateral distance of 10 meters. The surrounding rock is argillaceous fine to locally coarse bioclastic pale green-gray thin nodularly bedded limestone. The bioherms are irregular lenses 20–100 centimeters wide and 10–40 centimeters high. They are 1–3 meters apart although there are no bioherms for 100 meters or more beside this group. They consist of dense accumulations of favositids and laminar to low dom-

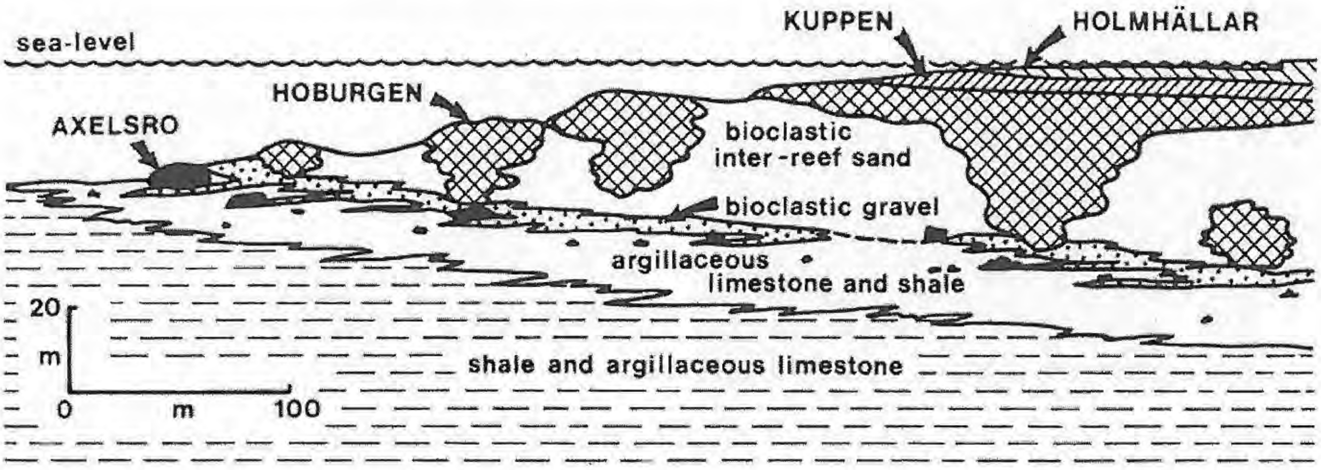

FIG. 23.—Idealized model of Gotland reef development.

ical stromatoporoids with some halysitids and fewer heliolitids. Small patches of bryozoans and *Syringopora* encrust some of the surfaces and there are scattered branched bryozoans, gastropods, and brachiopods (*Leptaena*, *Atrypa*, rhynchonellids) close to the larger skeletons. The individual favositids and stromatoporoids, which are the principal components, are up to 40 centimeters across, but most specimens are less than 15 centimeters.

An example is shown in Figure 24. This mini-reef occurs 12 meters south of, and 1 meter higher than, the two stromatoporoids figured in Kershaw and Riding (1978, fig. 13). It is composed mainly of halysitids and ragged laminar to low domical stromatoporoids. The large organism is a stromatoporoid 34 centimeters across. The adjacent limestone contains poorly-sorted bioclastic debris and away from the reef isolated halysitids and stromatoporoids occur, commonly 10 centimeters across. Quite commonly adjacent organisms are overturned indicating moderate current activity sporadically.

Larger examples of these bioherms are well seen in the shore section between Axelsro and Kneippbyn (Fig. 25). These include small structures similar to those at Halls Huk 3 but also larger ones up to 5 meters across. One of the small reefs on the shore due north of Kneippbyn and just outside the military shooting range is unusual

TABLE 2.—FEATURES OF GOTLAND REEF TYPES

	AXELSRO	HOBURGEN	KUPPEN	HOLMHÄLLAR
Environment (light & energy)	low	moderate	high	very high
Dominant organisms	tabulates, domical stromatoporoids	laminar-domical stromatoporoids, tabulates	laminar-domical-bulbous stromatoporoids	cuspate laminar stromatoporoids
Diversity	moderate	high	low	very low
Matrix	fine, argillaceous	fine-coarse, argillaceous	fine (draped)-very coarse	fine-very coarse
Geometry and size	bioherms (small)	bioherms (large)-biostromes	biostromes	biostromes
Structure	dense	dense-frame	dense-frame	frame-solid
Stability	moderate	low-moderate	high	high
Associated sediments	shale, argillaceous limestone, bioclastic gravel	bioclastic sand and gravel	bioclastic gravel, argillaceous limestone, shale	bioclastic gravel

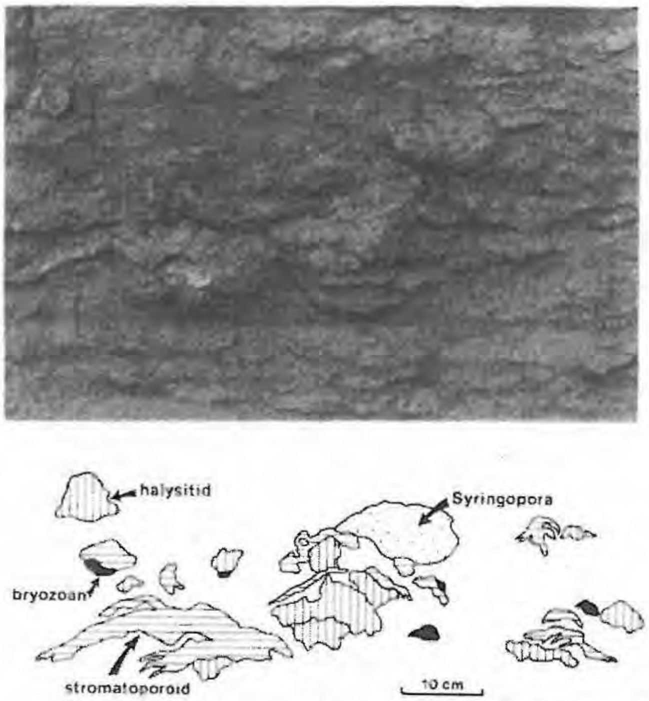

FIG. 24.—Small protobioherm of Axelsro type in the Visby Beds at Halls Huk 3, Gotland: photograph above, and map of organisms below (map courtesy of Ted Nield).

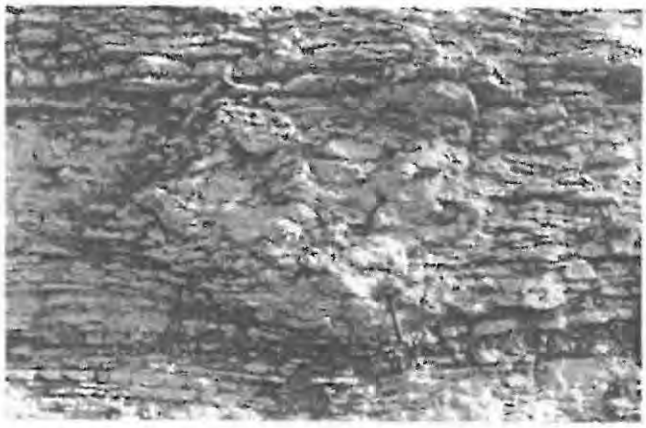

FIG. 25.—Axelsro bioherm showing "ballstone" structure and relationship to surrounding bedded limestones and shales: Upper Visby Beds between Axelsro and Kneippbyn, Gotland; hammer 28 centimeters long.

in being composed almost entirely of low domical stromatoporoids and a few favositid colonies (Fig. 26). In this area the Axelsro reefs occur in the Upper Visby Beds with at least one occurring every 50 meters along the section. They mostly range from 1–5 meters across and typically have an irregular lensoid form. Some occur with their basal surface on the argillaceous limestone which makes up most of the Upper Visby Beds, but many, especially the larger ones, rest upon very coarse bioclastic pebbly gravels which channel into the underlying argillaceous limestone. The gravel is made up mainly of large rugose and tabulate skeletons, with some stromatoporoids, up to 25 centimeters across in a bioclastic gravel matrix.

A biostrome formed by halysitids occurs in the Lower Visby Beds at Ireviken 3 (Stel, 1978b, p. 9–12). *Catenipora* colonizes a shale-limestone substrate and results in a *Catenipora, Favosites, Ketophyllum* association forming a bed 1.50 meters thick which is laterally extensive.

Small structures of Axelsro type also occur higher in the Gotland sequence in the Klinteberg Beds at Klinteberg (Manten, 1971, fig. 165).

Hoburgen Bioherms.—Hoburgen reefs show the greatest range of internal structure of Gotland reefs. They are essentially stromatoporoid reefs but they contain a diverse biota including rugosans, tabulates, bryozoans, brachiopods, calcareous algae, and gastropods. The stromatoporoids range from laminar to bulbous and extended domical forms but most commonly are low to high domes. Nevertheless, stromatoporoid morphology is less diverse than in the Kuppen reefs; there are fewer laminar and extended domical forms. The Hoburgen reefs have a relatively argillaceous matrix and this may have inhibited laminar forms, which are prone to covering by sediment, and extended domes which perhaps required a firmer and less unstable substrate. The matrix also includes coarse bioclastic limestone.

A feature of particular interest in Hoburgen reefs is the tendency toward a vertical succession from tabulate through stromatoporoid to coral-algal dominated sub-units (Nigel Watts, pers. comm., 1978). The tabulate dominated sub-unit resembles the Axelsro reef-type and Axelsro reefs do occur directly beneath Hoburgen reefs in regressive sedimentary phases such as the Visby-

FIG. 26.—Very small, stromatoporoid dominated bioherm; Visby Beds, Kneippbyn, Gotland; hammer 28 centimeters long.

FIG. 27.—Hoburgen type reefs at Högklint, south of Visby, Gotland. The lower, slightly recessive, part of the cliff is formed by Visby Beds (limestones and shales). The overlying Högklint Beds are here dominated by large bioherms which pass laterally (seen at right) into bedded bioclastic limestones.

FIG. 29.—Large bioherm (right) and adjacent inter-reef sediments (left) in Högklint Beds at Häftingsklint, northwest Gotland.

Högklint sequence. The coral-algal facies consists of large branched *Solenopora* growths with branched rugosans forming a frame structure.

Good examples of Hoburgen reefs occur in the Högklint, Klinteberg and Hamra Beds and on Lilla Karlsø. They are particularly well seen at many localities in the Högklint Beds along the northwest coast, in the Main Limestone on Lilla Karlsø and in the Hamra Beds at Hoburgen itself.

The abundance of Hoburgen patch-reefs is remarkable. They are common in each of the three major carbonate wedges, and Eriksson and Laufeld (1978, p. 27) counted over 500 in the Högklint Beds alone.

Högklint Beds.—The shales and argillaceous limestones of the Visby Beds are overlain by the Högklint limestones which give rise to steep cliffs along the northwest coast. Högklint (literally "high cliff") rises 35 meters above sea level and exposes lensoid Hoburgen reefs enclosed in bioclastic sands and gravels. Locally the gravels channel into the underlying Upper Visby sediments. Some reefs of Axelsro type continue from the Upper Visby into the Högklint but the majority of reefs are restricted either to the Visby or Högklint Beds. Those beginning in the Högklint are of Hoburgen type and form lens-shaped masses whose irregularly nodular to lenticular internal structure contrasts with the distinct bedding of the adjacent bioclastic limestone (Fig. 27).

At Högklint the bioherms are up to 50 meters wide and 25 meters thick, but larger individual reefs up to 300 meters across are well seen further north on the coast between Nyhamn and Irevik (Stel, 1978a, p. 115–127). Lower cliffs between these patch-reefs expose bedded inter-reef sediments (Fig. 28). The reefs occur every few hundred meters along this stretch of coast and are often present as tight clusters; at Häftingsklint 1–3 perhaps ten or more lenses make up what superficially is a single large reef (Fig. 29) (Nigel Watts, pers. comm., 1979).

The relationships between reef and off-reef limestone are well seen at Korpklint 1, near Snäckgärdsbaden (Fig. 30) where coalescive reef lenses irregularly overlie well-bedded crinoidal

FIG. 28.—Patch-reefs and intervening bedded limestones; Högklint Beds between Nyhamn and Irevik on Gotland's northwest coast; photo courtesy of Nigel Watts.

FIG. 30.—Hoburgen type bioherms overlying bedded bioclastic gravels in Högklint Beds at Korpklint, Snäckgärdsbaden, north of Visby, Gotland.

FIG. 31.—Bedded bioclastic gravel squeezed up between the bases of two adjacent bioherms by compaction. Högklint Beds, Korpklint 1, Gotland; photo courtesy of Nigel Watts.

FIG. 32.—Concentric lines on the wave-cut platform circling a patch-reef remnant reflect a compactional syncline (*"Philip Structure"*) in the Visby Beds beneath the reef. From Jungfrun, near Lickershamn, northwest Gotland; also see top of Figure 33 (photo courtesy of Nigel Watts).

limestones, and compaction has locally squeezed the bioclastic gravels upwards into invaginations between reef lenses (Fig. 31). In turn, the underlying Visby Beds are depressed to produce small compactional synclines. Arne Philip of Visby noticed these circular structures with diameters of 20–70 meters during flights over the wave-cut platform of the northwest coast where erosion has removed the Högklint Beds to reveal the compactional imprints of the patch-reefs upon the Visby Beds (Fig. 32). The occurrence of these *"Philip structures"* has been documented by Eriksson and Laufeld (1978) who realized their value in providing an indication of the spatial pattern of reef development in the Högklint and named them after their discoverer. They also proposed the term *"Cumings structure"* for the updoming of strata above bioherms (Eriksson and Laufeld, 1978, p. 20). Hede's maps give a good general impression of the distribution of the Hoburgen reefs in the Högklint Beds (see Eriksson and Laufeld, 1978, figs. 4–6), but many of the reef areas plotted by him are actually patches of numerous individual reefs (Nigel Watts, pers. comm., 1978). By using Arne Philip's aerial photographs Eriksson and Laufeld were able to map out the pattern of reef occurrences along the 100–200 meters wide cliff and wave-cut platform area of many parts of the northwest coast (Fig. 33) and convincingly demonstrate that many of the reefs are circular and have a non-linear distribution. They conclude that much of the Högklint coastal exposure is in a several kilometer wide patch-reef zone with thousands of individual bioherms (Eriksson and Laufeld, 1978, p. 28).

Although the majority of the Högklint reefs are lensoid in form, they do cluster together (as at Häftingsklint, mentioned above) and locally coalesce to form extensive biostromal masses. This condition is approached at Korpklint 1 and is well seen at Halls Huk. Between the village of Kap and Halls Huk 3 the cliff continuously exposes 1 kilometer of Högklint reef lenses overlying bioclastic limestones. The Upper Visby Beds are mostly covered by talus except at Halls Huk 1 and Halls Huk 3. For most of its length the cliff is capped by Hoburgen reefs which overlie, and pass laterally into, bedded limestones. The tops of the reefs are only seen where small patch-reefs terminate early in the Högklint sequence, but for the most part the cliff top bevels the reefs off. The bedded limestones range from medium-grained bioclastic thin-bedded limestones, often showing small scale planar cross-bedding and small (less than 2 meters wide) shallow channels, through gravels to thin to medium-bedded coarse pebbly deposits with fragments and whole skeletons of rugosans, tabulates and stromatoporoids up to 30 centimeters across.

The reefs here are bioherms 2–20 meters across which usually coalesce laterally to form a virtually continuous lenticularly based biostrome along the cliff top. The structure is dense to loose in its lower part and consists of large, low to high domical and bulbous stromatoporoids with rugose corals and abundant bryozoans, tabulates and brachiopods. Many of the high domical and bulbous stromatoporoids are on their sides and bulbous forms occasionally occur in coarse, bedded gravels, probably well away from their sites of growth. In between is a talus type deposit of moved, usually small, skeletons.

The upper parts of the reefs are not well seen due to lichen cover and weathering but are probably represented in fallen blocks north of Hallshuk 3 where low to extended domical stromatoporoids up to 35 centimeters across occur with tabulates, stick bryozoans and massive rugosans in a dense, possibly frame, structure.

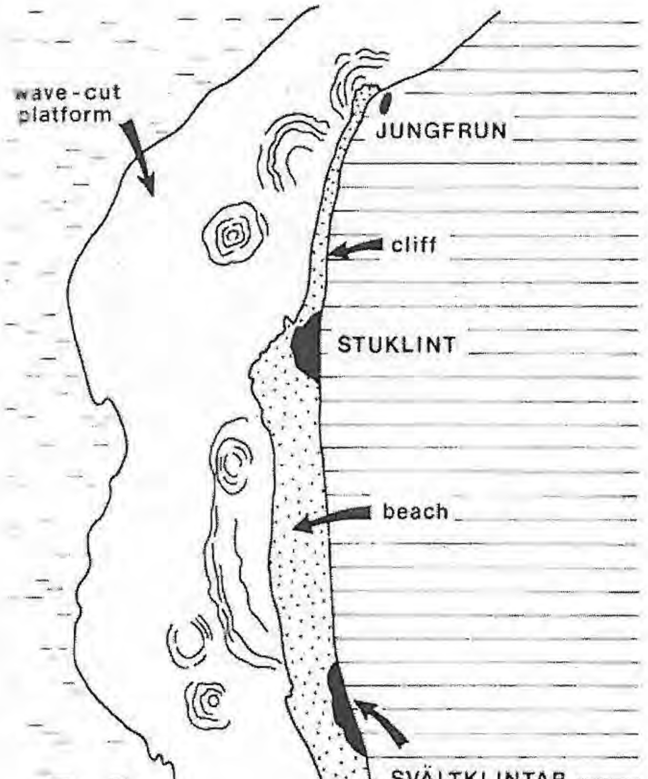

FIG. 33.—Distribution of "*Philip structures*" in the Visby Beds on the wave cut platform 25 kilometers north of Visby, Gotland. The remaining reefs in the Högklint Beds along the cliffs are marked in black (from Eriksson and Laufeld, 1978, fig. 15).

FIG. 34.—Cliffs of biohermal Hamra Beds at Hoburgen, southern Gotland. The hill in the center of the picture is immediately north of Storburg, and is capped by bedded limestones of the Sundre Beds.

There are few very good in place exposures of Hoburgen reef structure in the Högklint, or anywhere else on the island. Weathering and lichen cover obscures the reef structure, even where the immediately adjacent bedded limestones are very clean, and the reef is seen only as an irregularly nodular, rubbly or lenticularly structured mass in which a few large organisms and some of the matrix can be recognized but in which the distribution, composition and mutual relationships of the majority of the components are far from clear.

However, the fallen blocks near Halls Huk 3, together with blocks of laminar stromatoporoid frame at Ireviken 3, suggest that there is a vertical transition from dense to frame structure in the Hoburgen reefs of the Högklint Beds. This is confirmed by exposures in the Gutevägen area (Fig. 21) on the south side of Visby where Högklint reefs are capped by a coral-algal facies of stubbly branched solenoporaceans and branched rugosans forming a tight framework.

Between Gutevägen 3 and Gutevägen 2 reefs overlying bedded limestones are exposed in the upper part of a long low cliff. The underlying limestones range from wavy thin-bedded medium-grained sands with shale partings to coarser gravel units which are locally cross-bedded, and pass upward into medium-bedded coarse to pebbly bioclastic limestones immediately below the reefs. The reefs are up to 4 meters thick and occur as patch-reefs and coalesced patch-reefs forming biostromal units which may extend continuously laterally for up to 100 meters. Individual reefs are never separated laterally by more than 15 meters of bedded limestone.

The reefs consist of mid- to extended domical stromatoporoids up to 30 centimeters across with abundant branched rugosan colonies and scattered coenites. Most of the stromatoporoids are mid- to high domes, many are fallen. The extended domes are often non-enveloping.

For 100 meters or so north of Gutevägen 2 the reefs are overlain by *Solenopora* limestone followed by wavy-bedded laminar stromatoporoid limestone which together are up to 1.5 meters thick. At the road section (Gutevägen 2) the margin of the biostrome where it passes laterally into

FIG. 35.—Hoburgen type bioherms at the "type locality" showing large coalescive lenses passing laterally into bedded limestones; Hamra Beds at Hoburgen, center of Figure 34.

FIG. 36.—Dipping bedded limestones, possibly representing original depositional slopes, on the south side of Lilla Karlsö.

coarse-bedded limestone is rubbly and argillaceous with overturned mid-high domical stromatoporoids. On the west side of Gutevägen 4 the coral-algal facies is overlain disconformably by laminar stromatoporoid limestone representing bevelling and recolonization of the reef surface.

Hoburgen.—Near the southwesternmost tip of the island at Hoburgen, Storburg and three small hills east-northeast of it expose reefs in the Hamra Beds (Fig. 21). The reef rock itself is mostly lichen covered, but the extensive exposure shows the spatial distribution of the reefs and their enclosing sediment well (Fig. 34). The reefs overlie bioclastic limestone, including oncolitic limestone near its base, which rests on the Burgsvik Sandstone and Oolite (see Munthe, 1910, p. 1424–1425). They are also enclosed laterally and covered by bioclastic limestone, the overlying layers being referred to the Sundre Beds (see Laufeld, 1974a, p. 65; Munthe, 1910, fig. 22). These bioclastic limestones vary considerably in texture from coarse sands to conglomeratic gravels, with thin to thick-bedding, which are mainly composed of crinoids, coral and stromatoporoid debris. The seaward side of the first hill north of Storburg shows at least eight coalescive reef lenses (Fig. 35), each approximately 4 meters high and 8 meters wide, forming a patch-reef cluster 25 meters long and 16 meters high. Reef structure is best seen on the south side of this hill (Hoburgen 4, see Munthe, 1910, fig. 22) where a reef lens 10 meters thick and 25 meters wide, also forming part of this cluster, is composed of low–mid-domical stromatoporoids, commonly 30 centimeters across, with patches of argillaceous and bioclastic matrix. There is much general disorientation of the large skeletons and on the northwest side of this bioherm large to low-domical stromatoporoids up to at least 1 meter across are overturned at the lower margin of the lens. The enclosing bioclastic limestones form an abrupt contact with the reef.

Karlsö Islands.—The Karlsö Islands (Fig. 21), the largest islands off the western coast of Gotland, are distal southwestward continuations of the second main limestone wedge of the island, probably correlating for the most part with the Slite and Klinteberg Beds. On both Stora and Lilla Karlsö thinly-bedded shale-limestone sequences occur in the northwest and are succeeded by relatively thick limestone sequences consisting mainly of bedded bioclastic limestones surrounding patch-reefs. Manten (1971, p. 242–243) distinguished two reef types on Stora Karlsö different from those of Gotland: the Stäunasar type consists of corals and stromatoporoids, the Fanterna type of bryozoans and corals. I have not visited the localities after which these reef types are named but many of the Karlsö reefs are lenticular masses enveloped in bedded bioclastic limestones and they resemble the Hoburgen type. However, bryozoan biostromal limestones, formed by branched masses of *Coenites* in arcuate clusters up to 20 centimeters thick, occur near Smojge 1 on the northern side of Lilla Karlsø and large branched tabulate colonies, many overturned, are present south of Sudervagnhus on the west side of the island. These may resemble the Fanterna limestones of Stora Karlsö. But both islands are dominated by steep-sided plateaux of bedded bioclastic limestones enclosing lensoid patch-reefs. Following Rutten (1958), Manten (1971, p. 242 and 258) believes that these plateaux are cored by large reefs and he also recognizes "flank reefs" in the surrounding bedded limestone. It is difficult to test this idea of large central reefs and it is possible that the plateaux are constructed internally in much the same way as their margins, with scattered patch-reefs separated by bedded limestone.

The Karlsö outcrops are particularly interesting

FIG. 37.—Kuppen type biostrome, at the type locality, truncated by a disconformity and overlain by stromatoporoid-rich gravels; Kuppen 2, Hemse Beds, eastern Gotland. Hammer is 28 centimeters long; compare Figure 38.

because of the steeply dipping margins of the main limestone outcrop in some places, especially on the southern side of Lilla. Here the coarse bioclastic limestones, with a few incorporated patch-reefs, abruptly change from sub-horizontal to a dip of 30 degrees which can be followed through a height of at least 10 meters (Fig. 36). At the northwestern and western sides of the island large blocks of reefal and bioclastic limestone up to 30 meters across have slid into the underlying *Pentamerus gotlandicus* limestone (bioclastic limestone bands separated by shale) crushing and buckling it. Manten (1971, p. 273–275) regards this as probably due to Quaternary rock slides, but Sven Laufeld (pers. comm., 1978) considers it to be of penecontemporaneous Silurian age, and it is quite possible that the Karlsö Islands represent outliers of Klinteberg Limestone which were small carbonate platforms of bedded and reef limestone with steep marginal slopes to deeper water argillaceous sediments down which fragments of partly lithified limestone slipped to form megabreccias which deformed the soft basinal sediments.

Kuppen Biostromes

Manten (1971, p. 386) recognized that the reefs described here as Kuppen type do not fall neatly into his scheme of reef classification. Those near Herrvik, at Kuppen 1 and 2 (Fig. 21), he regarded as a variant of the Hoburgen type and those at Ljugarn and Fågelhammer he regarded as Holmhällar reefs. But the Kuppen reefs are significantly different from Hoburgen reefs, particularly in the diversity of the stromatoporoid morphotypes which they contain, and the relative paucity of other organisms. Equally, the Ljugarn and Fågelhammar reefs, except for the laminar stromatoporoid frame structure on the south side of Fågelhammar 1, commonly contain high and extended domical stromatoporoids whereas the Holmhällar type is characterized by laminar frame structure.

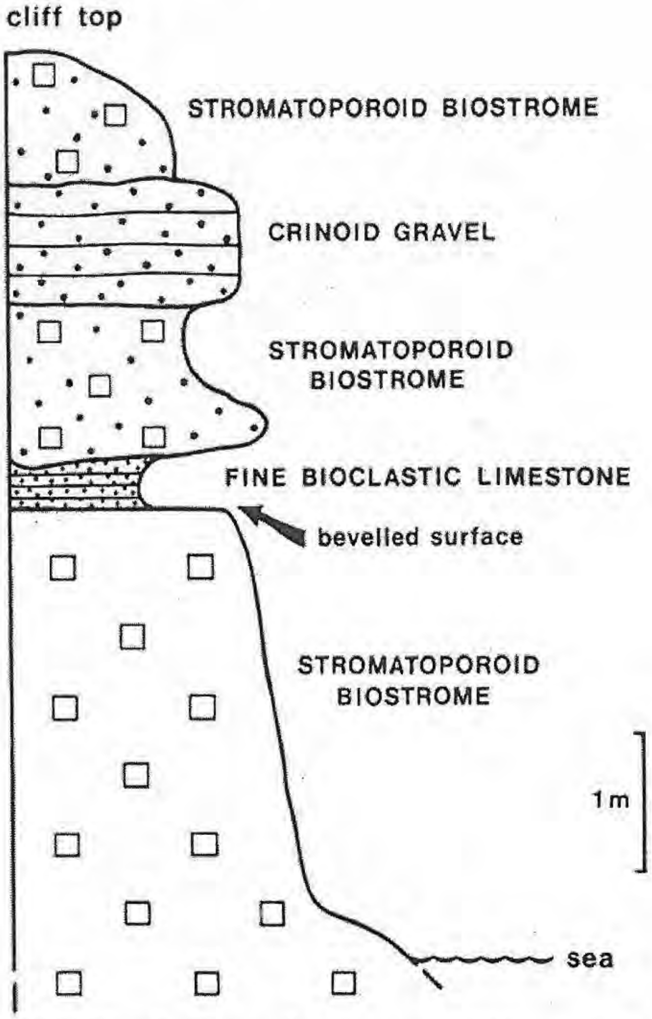

FIG. 38.—Sequence of stromatoporoid biostromes in the Hemse Beds at Kuppen 2, Gotland. The "type" Kuppen biostrome is the lowest unit; also see Figure 41.

The Kuppen type is a dense to frame biostromal deposit dominated by large laminar, low to extended domical and, occasionally, bulbous stromatoporoids in a relatively fine-grained grey-green argillaceous or crinoidal limestone matrix. There are occasional stick bryozoans and attached brachiopods, but little else between the stromatoporoids. Branched rugosans and *Syringopora* occur *within* stromatoporoids forming *Caunopora*-type intergrowths.

Kuppen reefs occur in the upper part of the Hemse Beds, particularly unit d of Hede (see Laufeld, 1974a, p. 11–12) in the Katthammarsvik-Ljugarn area of the east coast (Fig. 21). Near Katthammarsvik they occur at several localities, including those around Östergarnsberget (Gannberg, see Manten, 1971, p. 352–359), Grogarns

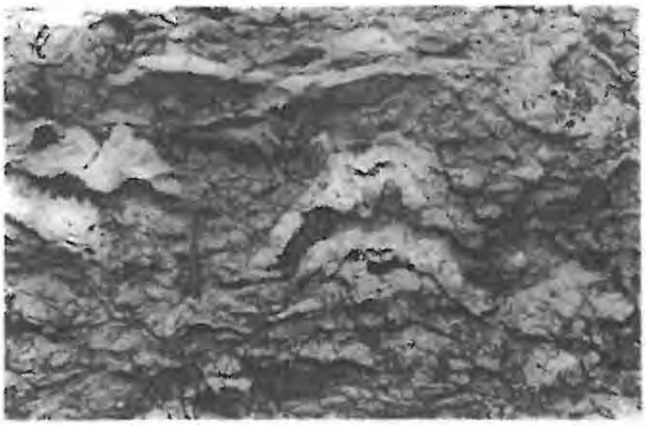

FIG. 39.—Kuppen biostrome structure showing the juxtaposed laminar and domical stromatoporoids. Close packing is enhanced by compaction, and many of the contacts are stylolitized: Kuppen 2, Hemse Beds, Gotland. Hammer is 28 centimeters long.

(Manten, 1971, p. 359–362) and Herrvik and form biostromes 5 meters thick and kilometers in lateral extent which are often dense rather than frame in structure.

Kuppen.—At Kuppen, east of Herrvik, a biostrome of this type, taken here as the typical example, is well exposed in sea cliffs (Munthe, 1910, fig. 28; Hede, 1929, p. 40–42). At Kuppen 2 (Fig. 37) the sequence (Fig. 38) is:

cliff top

5. 1.00 m+ stromatoporoid biostrome with crinoidal matrix,
4. 0.80 m bedded crinoid gravel,
3. 1.10 m stromatoporoid biostrome with crinoidal matrix,
2. 0.20–.40 m fine bioclastic limestone with stromatoporoid fragments,

flat bevelled disconformity surface

1. 3.40 m+ stromatoporoid biostrome with fine matrix,

sea level.

FIG. 40.—Laminar, domical and bulbous stromatoporoids at Kuppen 2: hammer is 28 centimeters long; detail of Figure 41.

FIG. 41.—Sequence at Kuppen 2 showing bevelled upper surface of the biostrome overlain by recessive fine bioclastic limestone.

Unit 1 is the biostrome of Kuppen type. It consists mainly of laminar to extended domical stromatoporoids forming a very dense to frame structure (Figs. 39 and 40). The laminar forms are up to 15 centimeters thick and the extended domes up to 80 centimeters high. The skeletons are separated by draped and laminated fine-medium grained argillaceous limestone patches up to 10 × 20 centimeters in size. Contacts between skeletons are usually stylolitized (Stephen Kershaw, pers. comm., 1976). The topmost 40 centimeters has smaller stromatoporoids and less fine matrix. This unit is truncated upwards by a smooth, flat erosion surface (Fig. 41) overlain by unit 2. Units 3–5 make up a stromatoporoid biostrome similar to unit 1 but with somewhat smaller laminar to extended domical stromatoporoids, abundant coarse crinoidal matrix, and a dense rather than frame structure.

Traced northwest around the coast these units continue for 100 meters virtually unchanged except that units 3–5 merge together. Seventy-five meters northwest of Kuppen 2 unit 1 is 4 meters thick and the base of the cliff exposes 1 meter of grey shale with thin laminar and high domical stromatoporoids. Here the lowest 20–40 centimeters of unit 1 has a coarse crinoidal matrix and the top 1 meter also has a coarser bioclastic matrix than the center of the biostrome which has the normal fine grey-green, draped fill. Beyond 100 meters northwest of Kuppen 2 the disconformity above unit 1 becomes less conspicuous and is replaced near Herrvik village by gravels below and a stromatoporoid bed above.

Fågelhammar.—At Fågelhammar 1, 3 kilometers north-northeast of Ljugarn, a rauk (erosional rock remnant) field exposes reef rock which on

FIG. 42.—Small isolated rauk (sea-stack) formed by a single domical stromatoporoid at Fågelhammar 1, Hemse Beds, eastern Gotland; hammer is 28 centimeters long.

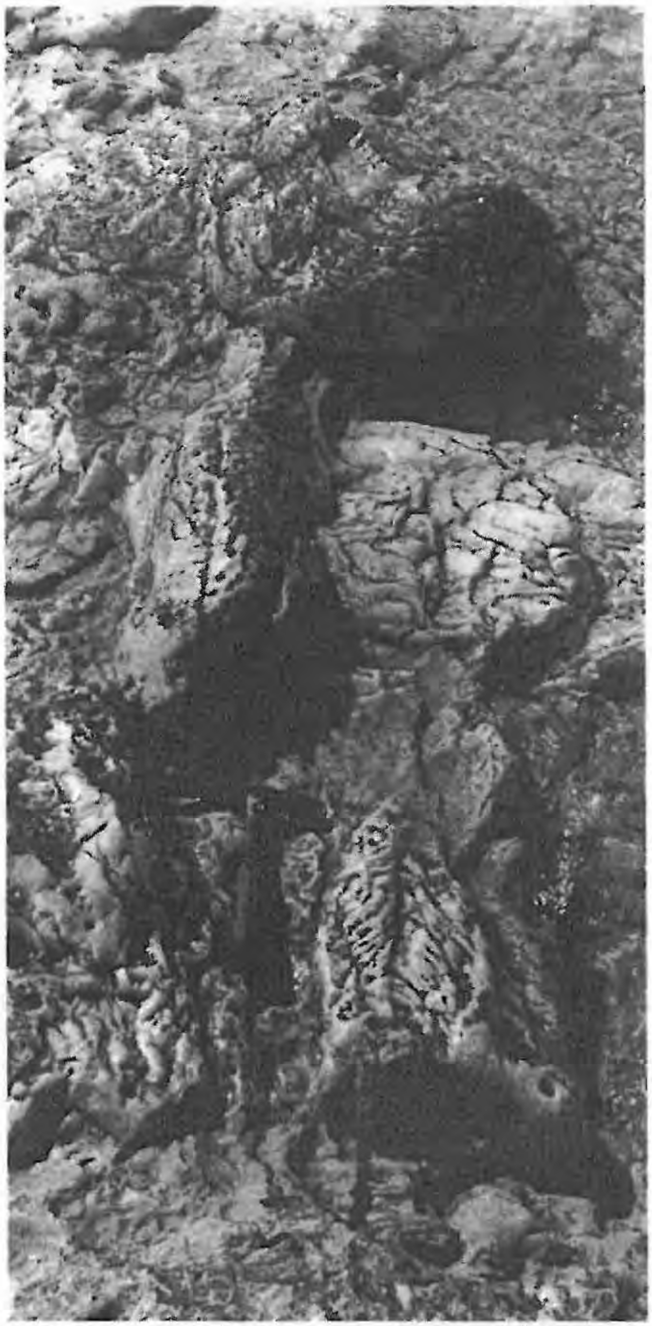

FIG. 43.—Toppled high and extended domical stromatoporoids associated with Kuppen type biostromes, Ljugarn, Hemse Beds, eastern Gotland; hammer is 28 centimeters long.

the north side of the locality consists of numerous large mid-extended domical stromatoporoids up to 1.5 meters across, many of which are toppled. One small rauk is a single extended domical stromatoporoid 1 meter high (Fig. 42). As at Kuppen they enclose branched rugose corals and tabulates and include grey-green draped matrix. There is a fair quantity of crinoid debris. On the south side the rauks consist of thin anastomosing, laminar stromatoporoid frame which resembles that seen in fallen blocks at Irevik 3 in the Högklint Beds of the northwest coast, and which also occurs in the Holmhällar reefs.

Ljugarn.—Northwards along the coast for 750 meters from the jetty at Ljugarn (Fig. 21) an eroded rauk field exposes reef of Kuppen type. At the northwestern end of the outcrop, 500 meters northwest of Ljugarn 1, shore line exposures show numerous high to extended domical stromatoporoids, often compound and often toppled (Fig. 43) together with laminar forms in a grey-green fine to coarse bioclastic, often crinoidal, matrix. The structure is less frame, and more dense, than Kuppen itself, due to the lesser abundance of stromatoporoids but they nevertheless constitute 30–40 percent of the rock.

These exposures are mainly in the plane of the bedding and this emphasizes the toppled domes whereas the Kuppen cliff exposures emphasize the laminar and low- to mid-domical forms.

The domical forms are up to 75 centimeters in height and compound specimens are up to 1.50 meters across. Draped fills are lacking. Further to

FIG. 44.—Rauk field (sea-stacks) representing dissected remnants of a Holmhällar type biostrome. The occurrence of enclosed hollows, and ridges parallel to the shore, suggest a karstic solution origin for the rauks with subsequent modification by littoral erosion processes; Holmhällar 1, Sundre Beds, southern Gotland.

FIG. 45.—Ground view of the Holmhällar rauk field shown in Figure 44.

the southeast, in the area up to 400 meters north of Ljugarn 1, the reef retains large domical stromatoporoids but they are less extended, more compound, less toppled and show delicate interleaving with fine matrix which suggests a gradual transition towards Holmhällar type.

Holmhällar Biostromes

These are stromatoporoid laminar frame structures which appear biostromal in form. Similar structures form parts of other reefs, as in the Kuppen type at Fågelhammar 1 and in the Hoburgen type at Irevik 3, but the Holmhällar type itself is extensively developed in the Sundre Beds, high in the Gotland succession, at a few localities near the southern tip of the island. These occurrences are in raukar fields which expose the limestones well laterally but in which the vertical exposure is limited to only a few meters. Also, the rauks are usually somewhat weathered and lichen covered and the details of the reef structure are not often very clear.

Holmhällar.—At Holmhällar 1 the extensive rauk field (Figs. 44 and 45) exposes frame reef rock composed of relatively thin anastomosing laminar stromatoporoids with coarse sand- to gravel-sized bioclastic matrix and occasional small lenses of finer green-grey poorly laminated sediment. The entire exposure, 800 meters long and up to 70 meters wide, is lithologically remarkably homogeneous and, in contrast to the Kuppen reef type, large domical stromatoporoids are very rare; only occasionally are high domes up to 30 centimeters in height seen. Rugose corals occur within some of the stromatoporoids, as at Kuppen, but there are no other conspicuous reef formers and the rock is dominated by laminar stromatoporoids. These are thin, usually 2–10 centimeters in thickness, wavy, and laterally ragged. Their upper surfaces are often very undulose and even cusped and locally rise into miniature high domes up to 15 centimeters in height (Fig. 46). They split laterally and overgrow one another to form a tight frame in which organisms constitute 40–60 percent of the volume. There are no large sparite-filled cavities. Crinoid fragments up to 5 millimeters across make up most of the matrix, but locally much larger crinoids with stems up to 3 centimeters in diameter occur.

Manten (1971, enclosure 2) provides a 1:1000 plan of the Holmhällar rauk field on which he identifies many of the larger rauks by number. They are generally less than 4 meters high. The greatest stratigraphic thickness occurs immediately west of rauk 228 (the reference point for Holmhällar 1 in Laufeld, 1974b, fig. 9) where up to 6 meters of reef is exposed. Even here there is no obvious vertical sequence. The rock shows a crude layering due to the laminar frame structure and dips gently, about 3 degrees, to the southeast. Near the center of the rauk field, in the vicinity of rauk 137, crudely-bedded coarse crinoid gravels with rolled stromatoporoids at their base overlie the reef rock disconformably. At rauk 137B the gravel erosively channels into the reef with up to 1.5 meters of relief.

The reef here is also traversed by a number of narrow (approximately 50 centimeters wide) vertical fissures filled by coarse crinoidal gravel which appear to radiate from a point approximately 250 meters inland. The fill may be of uppermost Silurian (Pridoli) age on the basis of conodonts (Lennart Jeppsson, pers. comm., 1979). At the side of rauk 137B the fissures also appear to cut the coarse gravel overlying the reef.

At Holmhällar the reef deposits, which belong to the Sundre Beds, must almost directly overlie the Hamra reef horizon exposed at Hoburgen 10 kilometers to the west. Manten (1971, p. 189) believed the crescent-shaped outcrop of the Holm-

FIG. 46.—Laminar stromatoporoid frame structure of the Holmhällar biostrome at Holmhällar, Sundre Beds, southern Gotland. Commensal rugosans, crinoid gravel, and lack of diversity in either form or biota are consistent with a high energy environment in which stromatoporoids formed laterally anastomosing flattened or wavy sheets; hammer head is 17 centimeters long.

FIG. 47.—Partial aerial view of the Holmhällar rauk field, southern Gotland, showing the crescentric shape with beach-ridges behind.

hällar rauk field (Fig. 47) reflects the original plan of the reef and he regarded Holmhällar reefs, generally, as having this form. This is possible, but the absence of exposures of any lateral off-reef sediments makes it difficult to confirm or deny this interpretation. Rocky headlands on Gotland, as anywhere else, tend to be arcuate and this seems just as likely an explanation of the form of the rauk fields. The Holmhällar field is 500 meters from tip to tip of the crescent and the Hammarshagehällar rauk field 1 kilometer across the bay to the northeast is even larger. The Hammarshagehällar rock has a somewhat lesser volume of in place organisms and more matrix, but it is otherwise similar to that at Holmhällar and is composed essentially of laminar stromatoporoids and crinoid debris. The two outcrops could quite conceivably be parts of the same biostrome, and Holmhällar biostromes, like those of Kuppen type in the Östergarn district, could extend laterally for several kilometers.

Other Localities.—Manten (1971) included several rauk fields in the Hemse Beds, such as those at Ljugarn and Fågelhammar, in the Holmhällar reef type. Possibly the development of crescentic rauk fields at these localities encouraged him to do this, but the limestones themselves are only generally similar to Holmhällar itself in being biostromal; the stromatoporoids which dominate them have quite a different form and size. They are here (see above) included in the Kuppen type.

However, there is an element of transition locally between Kuppen and Holmhällar types, as already noted near Ljugarn 1. This is to be expected if the environmental synthesis (presented below) suggesting the Holmhällar type to be a higher energy reef than the Kuppen type is correct since they are both relatively shallow water biostromal reefs. But in the principal examples exposed on Gotland the two types remain very distinct. Similarly, transitions occur between the Axelsro and Hoburgen reefs and although they are rarely exposed, between the Hoburgen and Kuppen types.

Model of Gotland Reef Development

The four main reef types described here from Gotland fit together into an environmental pattern which, ideally, can be seen within one phase of reef growth and which can also be placed in a broad stratigraphic-sedimentologic context allowing comparison with Silurian reefs in other areas (see Discussion). In other words, they are not isolated and mutually unrelated structures but represent responses of sessile organisms in the Silurian Baltic shelf sea to environmental variables which have imposed patterns and trends upon them. This can be seen most simply in vertical facies changes which reflect original lateral variations correlated with depth.

The enclosing sediment, biota, size, and geometry of the reefs described above suggest that the Axelsro, Hoburgen, Kuppen, and Holmhällar types are stages in the response of reef building organisms to progressively shallower and more turbulent conditions (Fig. 48). However, only part of this sequence (the Axelsro-Hoburgen transition of the Visby and Högklint Beds) appears at present to be seen continuously in vertical section, and so the model presented here is interpretive and provisional (Fig. 23).

In the Upper Visby to Högklint Beds sequence of the northwest coast the transition from Axelsro to Hoburgen reefs is clearly seen (Ted Nield and Nigel Watts, pers. comm., 1979), but the replacement of Hoburgen dense reef structure by frame reef in the upper part of this succession is only shown at a few localities, such as Gutevägen 2 and 4, due to both penecontemporaneous and Re-

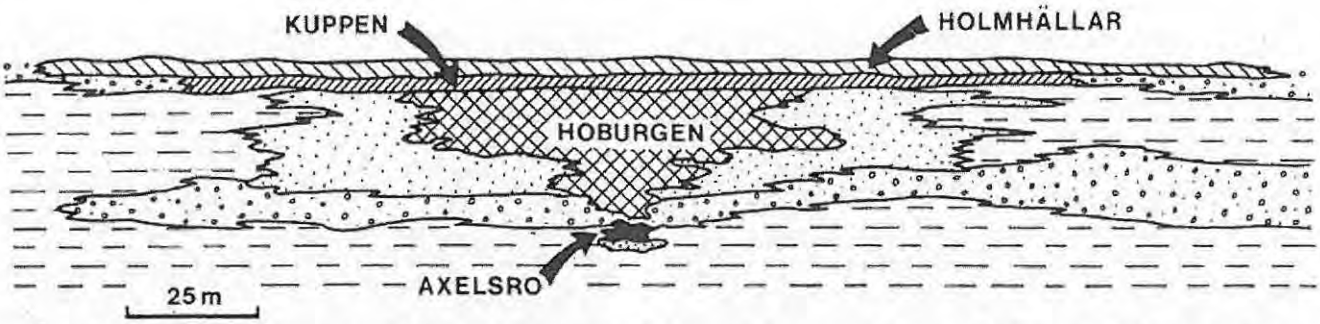

FIG. 48.—Size, geometry, associated sediments and inferred relative positions of bioherm and biostrome types in a shallowing-up sequence. Incidence of laminar organisms, frame structure and rigidity increase upwards.

cent erosion. Similarly, the upper part of Hoburgen reef development is eroded at Hoburgen itself (Storburg 2 and Hoburgen 4), but the Sundre Beds are only approximately 10 meters thick according to Hede (1960, p. 47) so that the equivalent of the Holmhällar reef exposed at Holmhällar 1 must originally have been directly above this horizon at Hoburgen. Although no exposures of Hoburgen reef passing into Kuppen or Holmhällar type are known at present it is suggested here that such a transition is to be expected. The basis for this reasoning lies in the interpretation of the environments of deposition of the reef types. The coarseness of the associated sediments, the tightness of the reef structure and the tendency towards a biostromal form all generally increase from Axelsro to Holmhällar type. In the same sequence there is a trend toward a reduction in biotic diversity and a greater likelihood of erosion of the reef surface. The reef matrix remains fine throughout, but the Kuppen and Holmhällar types are characterized by a reduction in argillaceous matrix and a tendency towards draping of the fill, suggesting filtering of fines down through a relatively tight organic framework. These features are consistent with the suggestion that Axelsro, Hoburgen, Kuppen, and Holmhällar types represent a spectrum of structures grading away from relatively deep, quiet water conditions of reef growth (Axelsro type) towards turbulent, shallow water where rigorous conditions resulted in low diversity, strong, biostromal reefs prone to exposure and erosion (Holmhällar type) (Fig. 23).

The shallow water conditions of formation inferred for the Kuppen and Holmhällar reefs limited upward growth, enhancing biostromal form in contrast to the bioherms of the Axelsro and Hoburgen types, and created the possibility of periodic exposure and resubmergence. The resulting erosion provided bevelled surfaces for subsequent recolonization, as seen at Kuppen 2, and so erosion had the effect not only of removing the upper surfaces of biostromes but also of providing areas for them to become established on. This disrupted trends in vertical reef development and made it unlikely that a complete, unbroken sequence showing all four phases of reef growth could be preserved. Instead, a sequence with upper biostromes bounded vertically by disconformities (Fig. 48) is more likely to occur.

Organism type and form, biotic diversity, matrix and surrounding sediment composition and texture, as well as reef structure and geometry thus are all thought to reflect gross environmental constraints which are probably basically depth related. Detailed paleoecological considerations are outside the scope of this broad synthesis approach, but it can be noted that tabulates were more successful in quieter, muddier water (Axelsro type), and that stromatoporoid form becomes distinctly laminar in turbulent conditions (Holmhällar type). Highest diversity is shown in Hoburgen reefs, intermediate in the trend deduced here, and is lowest in the Kuppen and, especially, Holmhällar types where rugosans and tabulates were obliged to grow within stromatoporoids, presumably for physical support and protection. Calcareous algae, particularly solenoporaceans, are prominent in the upper levels of some Hoburgen reefs, as at Gutevägan 4. Manten (1971, p. 188) considers algae to be a significant component of the Holmhällar reefs, but he does not identify them more precisely.

Reef distribution can also be viewed in the context of the Gotland sequence as a whole (Fig. 4). Essentially, reefs appear to have developed abundantly at the seaward margins of the carbonate wedges but also occur well within them in association with coarse bioclastic, oolitic, and fine-grained, sometimes oncolitic, limestones. Basinward, argillaceous limestones, calcareous shales and mudstones were deposited. Manten (1971, p. 26) suggests that the coastline was generally to the northwest, trending northeast-southwest. But the configuration of the wedges rather suggests that they are thinning southwards indicating a coast to the north which was roughly trending east-west, although of course it is unlikely that any coast in this situation would have been linear in detail. The overall paleogeographic situation was one in which prograding carbonate wedges built out southwards (or southeastwards) into a shallow partially enclosed basin which deepened towards the Oslo-Baltic Syneclise. Carbonate progradation was accompanied by temporary exposure of the proximal carbonate belt, resulting in subaerial erosion. This is shown in the Högklint-Slite wedge by disconformities associated with the base of the Tofta Beds and indicates the regressive nature of this carbonate progradation. It was followed by a transgressive phase in which facies belts shifted northwards, resulting ultimately in the shale depositional environment moving over the underlying carbonate wedge. This pattern is repeated two or three times so far as the Gotland sequence is concerned and the overall sense of movement was regressive with successive carbonate wedges migrating southwards (Fig. 20). This is consistent with the general trend over the whole of the European craton towards the gradual establishment of terrestrial conditions by the Lower Devonian. Similarly, the distinct north-south polarity shown in the facies belts associated with the first two carbonate wedges (Högklint-Slite and Halla-Klinteberg-Hemse) appears to be breaking down in the upper part of the sequence. This could be due to a shallower, more embayed, mosaic facies pattern developing as the final regression approached, or to increased erosion removing the basal part of the third (Burgsvik-Hamra-Sundre) carbonate wedge. This latter interpretation is based on the possibility that extreme erosion during the regressive phase of carbonate development will locally strip off the entire lower part of the wedge so that subsequent transgression will take place over noncarbonate deposits. Stel and de Coo (1977) have interpreted the upper Burgsvik and lower Hamra-Sundre Beds in southern Gotland as transgressive deposits encroaching over a northeast-southwest trending shoreline (Stel and de Coo, 1977, figs. 27 and 28). It is suggested here that erosion removed preceding carbonate deposits in this area so that the third wedge is substantially thinner than it would otherwise have been. This wedge is thus anomalously thin for Gotland, although it should be emphasized that the preservation of the regressive sequences in the other carbonate wedges is really an unusual feature, peculiar to the Gotland sequence. Progradation of carbonate sediments due to the volume of carbonate production, closely dependent upon extensive reef development (as noted by Laufeld, 1974b, p. 7), seems here to have been at least as important as actual regression in constructing the wedges.

Over much of the shelf during carbonate deposition, patch-reefs of Hoburgen type developed in enormous numbers with inter-reef sediments of surprisingly low biotic diversity between them. Eriksson and Laufeld (1978, p. 28) estimate that thousands of small Hoburgen bioherms exist in the Högklint Beds and suggest, with Hadding (1956), that larger reefs occupied a zone on the open sea side of them.

Beyond this must have been a zone of Axelsro reefs forming in quieter water and preferentially forming on tongues of crinoidal debris thinning basinward. Nearer shore, probably in a narrower belt than the extensive Hoburgen patch-reefs occupied, Kuppen and Holmhällar biostromes colonized shallow and relatively turbulent environments possibly, if Manten's (1971, p. 189) view is correct, they were crescentic in plan. The Holmhällar reefs in particular suggest a very shallow environment which could have been a fringing-reef or a barrier, but there is no evidence at present of back-reef environments associated with them.

Estonia

Bioherms are reported at a number of levels in the Silurian of the eastern Baltic, principally in the lower Llandovery (G1–2), upper Wenlock (J2) and middle Ludlow (K2) (Kaljo, 1970, p. 340–342, fig. 81, 85, and 87). The paleontology of important reef building organisms such as stromatoporoids (Nestor, 1964 and 1966), and tabulates (Klaamann, 1962) has been well documented in the area, but I know of few detailed studies of the bioherms themselves.

Outcrops in Estonia (Fig. 19), together with borehole data from areas to the south in Latvia and Lithuania, indicate a relatively complete Silurian sequence which is wholly in marine or marginal marine facies and is 280–640 meters thick (Kaljo, 1970, p. 340–342). The Baltic coast of the USSR is only 150 kilometers east of Gotland and there are close similarities between the Silurian sequences of the two areas. The eastern Baltic succession accumulated in a broad embayment northeast of the Oslo-Baltic Basin which Nestor and Einasto (1977, fig. 1 and p. 119) regard as a pericontinental sea. As in Gotland the "most general trend in the development of the East Baltic Basin was the gradual regression of the sea, only at times interrupted by relatively short transgressions" (Kaljo and Jürgenson, 1977, p. 148). Kaljo (1970, p. 343) recognizes three major sedimentary cycles in the sequence and emphasizes tectonic control over deposition in the area. Three general episodes of siltstone-shale deposition occur: during the lower Llandovery, upper Llandovery, and upper Ludlow, and can be correlated with transgressions (Kaljo, 1970, p. 330–331). Facies analysis reveals a clear shelf-basin polarity in which bioherm development was located above wave-base in the inner shelf zone (Nestor and Einasto, 1977, fig. 3).

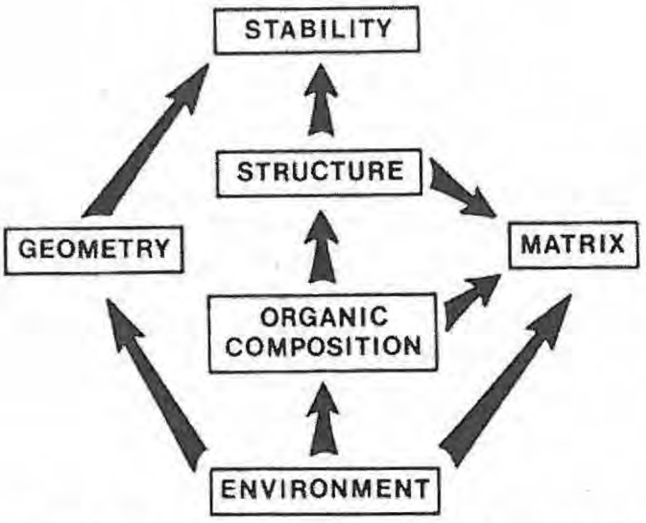

FIG. 49.—Principal interrelations of reef controls and effects.

FIG. 50.—Broad trends in the character and distribution of Silurian reef sequences in northwestern Europe.

Carbonate rocks accumulated mainly in the northern and northeastern parts of the area and consequently dominate the Estonian outcrops, while to the south and southwest calcareous and graptolitic shales were deposited (Kaljo, 1970, figs. 80–89; Kaljo and Jürgenson, 1977, figs. 1–8). In contrast to Gotland, dolomites and partly dolomitized limestones are present (Kaljo, 1970, p. 330) and clayey dolomicrites form the near-shore facies belt of the sequence (Nestor and Einasto, 1977, p. 120–121), e.g., in the lower Ludlow of southern Saaremaa (Kaljo, 1970, p. 341, fig. 86). Bioherms occur in the next zone seaward from this, associated with skeletal, oöid and peloid grainstones (Nestor and Einasto, 1977, p. 120).

Aaloe and Nestor (1977) describe bioherms from the lower Llandovery of the Ridala Peninsula and the island of Hiiumaa (Fig. 19) on the western coast of Estonia. They occur at two levels. The lower ones are very small aulocystid-algal structures in the Ridala Member (G1–2R), a discontinuous unit only 1–2 meters thick (Aaloe and Nestor, 1977, figs. 2–4). Less than 10 meters above this, larger bioherms occur in the Hilliste Member (G1–2H) which is up to 7 meters thick. These are relatively complex and variable structures up to 8 meters or more across (Aaloe and Nestor, 1977, fig. 8), composed of tabulates, stromatoporoids, colonial rugosans, algae, bryozoans and heliolitids, and associated with crinoidal limestones. These bioherms appear to be broadly comparable with those of Axelsro type in Gotland.

DISCUSSION AND SYNTHESIS

Gotland provides the key to understanding the Silurian reefs of western Europe because it contains by far the most complete spectrum of structures, from deeper water tabulate dominated argillaceous bioherms (Axelsro type) through Hoburgen bioherms and Kuppen biostromes to the shallow water, low diversity, stromatoporoid frame biostromes of Holmhällar type. These varieties of in place skeletal accumulation were generated by interaction between the local physical environment and the type of sessile calcareous organisms available at the time. Between them, environment and organisms controlled the structure, geometry and other features of the reefs (Fig. 49).

Reef Types

The naming of reef varieties after localities, as has been done for Gotland, brings to mind the proliferation of rock terms in igneous petrology and is not a welcome course of action. But in the absence of a comprehensive nomenclature of reef description and classification it is difficult to avoid. It does have the advantage of compressing numerous compositional and structural features into a single name, and provided that the temptation to progressively split types to take account of only minor variations is resisted then the scheme may have long term value.

To the four main Gotland reef types (Axelsro, Hoburgen, Kuppen, Holmhällar) can be added the thin, tabulate dominated biostrome seen at Irevik in the Lower Visby Beds which has counterparts in the Steinsfjord Formation of the Oslo Region. The Fanterna and Stäurnasar types of the Karlsø Islands require further study. Axelsro-type bioherms occur at Wenlock Edge in the Welsh Borderland and the Hilliste bioherms in the lower Llandovery of Estonia are probably also of this type. Most of the Oslo Region bioherms also appear to be of Axelsro type. The lower Wenlock bioherms of Ringerike, such as those on the west side of Geitøya, however, are distinct variants characterized by abundant *Girvanella*, *Rothpletzella*, and *Wetheredella*. These encrusters are common in Axelsro-Hoburgen reefs but are not usually dominant organisms.

So the picture which emerges is that the great majority of Silurian reefs in northern Europe can be compared directly with those seen on Gotland but that the latter include at least two major types (Kuppen and Holmhällar) not seen elsewhere. Examples in England and Norway can only be compared with Axelsro (plus the Irevik variant), and possibly the dense and less frame parts of Hoburgen reefs. The Estonian reefs are too poorly known to make real comparisons at present. Thus, it seems that reefs outside the Baltic area represent only the deeper, muddier varieties of a spectrum continuing in Gotland into shallower and more turbulent conditions.

Environment and Distribution

Silurian reefs developed in shallow, probably photic, carbonate environments often with high admixtures of argillaceous material. The organisms were capable of colonizing muddy substrates, but most of them show a preference for gravel bases such as the crinoid lenses below Axelsro reefs at Wenlock Edge and on Gotland and the crinoid limestones flooring the Hoburgen reefs of the Högklint Beds. The on-craton situation meant that regional sea floor topography was subdued. The only evidence of significant slopes associated with reef facies in the area at this time that I know of is on Lilla Karlsø, west of Gotland. Degree of water movement probably ranged from low to moderate around Axelsro reefs to very high over Holmhällar biostromes. The rigidity and stability of the reef structure increased along this gradient.

Spatial Distribution.—Enhancement of reef development cratonward, and away from the Caledonian mobile belt, correlates with increase of carbonate sedimentation and thinning of the total marine sequence (Fig. 50). Reef growth was clearly favored by the shallow conditions with low influx of siliciclastic sediment which were maintained for long periods in the Baltic area. This allowed a wide spectrum of reef types, deeper and shallower, patch and linear, to form. Closer to the mobile belt, in England and Norway, deeper water and sediment influx inhibited reef growth and restricted its scale and diversity.

The local lateral distribution of reefs in any one area is best inferred from their vertical distribution in time (see below) but both in the Wenlock Limestone of the Welsh Borderland and in the Högklint Beds of Gotland large areas, probably 1000 square kilometers or more in extent, were covered by patch-reefs and inter-reef sediments. Thin, but extensive biostromes developed both in the Oslo Region and in Gotland. Reef belts were fronted by deeper shale accumulating environments and backed by either low- or high-energy peritidal facies. The Gotland sequences promise to provide detailed records of the spatial distribution of these environments but, to date, facies analysis of them has barely begun and whether the Kuppen and Holmhällar biostromes, which probably were linear reefs, were near- or offshore in position is uncertain.

Vertical Distribution.—Reefs are associated with both shallowing-up (regressive) and deepening-up (transgressive) carbonate sequences and are limited mainly to the shallow subtidal portions of them. In Gotland reef development appears to have been concentrated in the outer zones of carbonate wedges adjacent to the outer shelf shales (Fig. 20). The inner parts of the wedges are dominated by peritidal and shoal carbonates and are preferentially associated with disconformable truncations of the sequence which locally bevel reefs.

The idealized reef succession in a regressive sequence presented in the model of Gotland reef development is inferred from disjointed sequences on the island; the most complete of which occurs in the Visby-Högklint Beds of the northwest coast. In England and Norway only the lower parts of this sequence occur, the remainder failing to develop due to adverse environmental conditions. The Gotland model can be used to predict what could have happened in some of these other areas if conditions had been different. For example, at Wenlock Edge the shallowing upward sequence from Wenlock Shale to Wenlock Limestone accompanied by development of Axelsro-type bioherms is directly comparable with the Visby-Lower Högklint Beds sequence on Gotland. The crinoid grainstones (facies D, "gingerbread") at Wenlock have their counterpart in the crinoidal limestones at the base of the Högklint Beds. But whereas, at Wenlock, these gravels appear to terminate reef development, on Gotland they can be seen to represent only a pause in reef formation since they are succeeded directly by the larger and compositionally and structurally more complex Hoburgen reefs of the main Högklint sequence. The gravels represent a crinoid shoal belt prograding outwards over the Axelsro reefs and ahead of the Hoburgen bioherms. Consequently, Scoffin's (1971, p. 216) conclusion that "extreme shallowing terminated reef development in the area" at Wenlock Edge needs to be modified in the light of the Gotland succession. The "gingerbread" facies may well have been succeeded by enhanced reef formation if it had not been for the deposition of the silts of

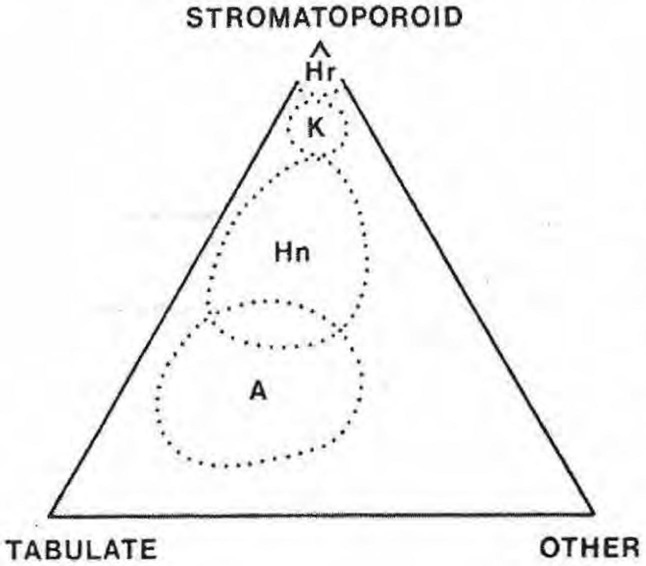

FIG. 51.—Estimated relative organic composition of reef types in terms of main and accessory builders. "Other" includes algae, rugosans, and bryozoans; A, Axelsro; Hn, Hoburgen; K, Kuppen; and Hr, Holmhällar.

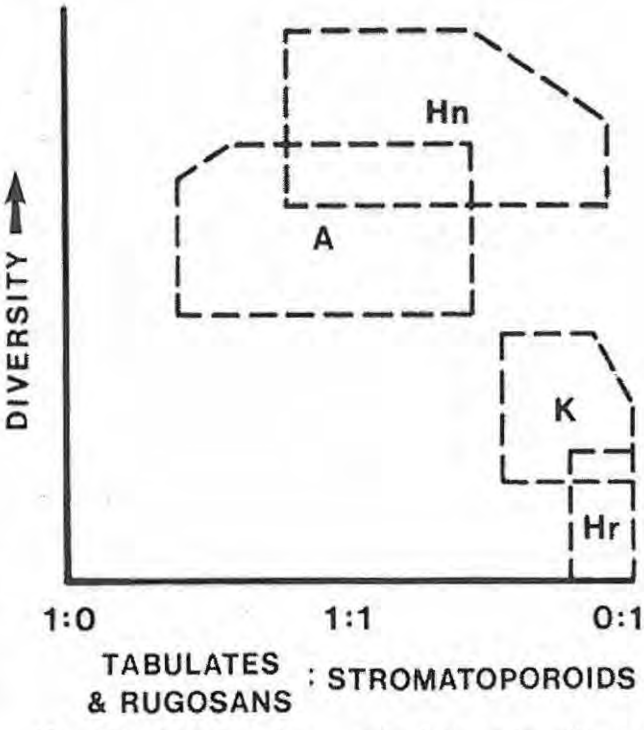

FIG. 52.—Rough estimates of relative diversity and major organism composition in the main reef types: A, Axelsro; Hn, Hoburgen; K, Kuppen; and Hr, Holmhällar.

the Elton Beds. There is no evidence of "extreme" shallowing at Wenlock and reef growth failed to resume because of a regional influx of fine siliciclastic sediment. This latter was the main factor responsible for poor reef formation everywhere adjacent to the mobile belt.

The vertical succession of reef and related facies mirrors their spatial distribution and, where the sequence is relatively complete, as on Gotland, indicates the original lateral variation in composition, structure and geometry of the reef masses. In the shallowing-up Visby-Högklint sequence Axelsro reefs occupied an off-shore belt adjacent to the deeper shelf muds. They passed shorewards into crinoid shoals and then Hoburgen patch-reefs with restricted lagoonal/inter-reef sediments (Fig. 23). Upper coalescence of the Hoburgen bioherms in the Högklint Beds into biostromal masses may reflect the existence of linear reefs of fringing or barrier type separating the patch-reef complex from a peritidal beach or tidal flat environment. The thinness of exposed sequences associated with Kuppen and Holmhällar biostromes and their truncation by erosion surfaces hamper similar analysis, but these biostromes are interpreted to be higher energy varieties of the linear reefs capping the Högklint sequence.

Composition

Organisms.—Tabulates and stromatoporoids are the major groups of reef builders present in the Silurian of northern Europe and they represent two ends of a compositional spectrum (Fig. 51). Axelsro type biostromes and small bioherms are tabulate dominated. Holmhällar biostromes are almost solely built by stromatoporoids. Larger Axelsro bioherms, Hoburgen reefs, and Kuppen biostromes contain different proportions of these organisms. The principal genera involved in reef construction are the stromatoporoids *Actinodictyon, Actinostroma, Clathrodictyon, Densastroma, Labechia, Parallelostroma, Plectostroma, Stromatopora*, and *Syringostroma* (Scoffin, 1971; Mori, 1968, 1970; Steve Kershaw, pers. comm., 1979), and the tabulates *Alveolites, Favosites, Halysites, Heliolites, Syringopora*, and *Thecia*. In addition rugose corals (such as *Acervularia, Amplexopora, Entelophyllum, Phaulactis*), calcareous algae (*Girvanella, Solenopora*), algal *Problematica* (*Rothpletzella, Wetheredella*), and bryozoans (*Coenites, Fenestella, Fistulipora, Hallopora, Rhombopora, Thamniscus*) are present, usually in lesser quantities. Rugosans and bryozoans are prominent in Axelsro and Hoburgen reefs, calcareous algae are conspicuous in some Hoburgen reefs. *Rothpletzella* and *Wetheredella* form crusts in Axelsro and Hoburgen reefs and are dominant in some of the lower Wenlock bioherms at Ringerike, Norway. Non-skeletal stromatolites described by Scoffin (1971) in the Wenlock Edge reefs may also be important elsewhere but have yet to be reported.

?Spirorbid worms are common, but tiny, additions to the reef mass and free living gastropods such as *Euomphalopterus* and *Euomphalus* (Ted Nield, pers. comm., 1979) are additional inhabitants. Reef associated brachiopods include *Atrypa*, *Camarotoechia*, *Cyrtia*, *Delthyris*, *Dicoelosia*, *Eospirifer*, *Leptaena*, *Platystrophia*, *Rhynchotreta* and many more (Manten, 1971; Bassett and Cocks, 1974).

Diversity of preserved organisms increases from moderate in Axelsro bioherms to high in Hoburgen, but then reduces dramatically in Kuppen and Holmhällar biostromes (Fig. 52). Similar trends of increasing diversity with shallowness, followed by reduction in the more rigorous surf-zone, are shown by Recent scleractinian reef communities. The stromatoporoids which dominate the Kuppen and Holmhällar biostromes appear to have been the only organisms capable of flourishing in these high energy conditions.

The success of stromatoporoids in shallow reef environments can be attributed mainly to their size, strength and, probably, relatively rapid rates of growth. But they were also apparently tolerant of loose sediment, both coarse and fine, and readily grew laterally to recolonize sediment deposited on the edges of coenostea producing *ragged* margins (Kershaw and Riding, 1978, p. 234). Tabulates appear to have been even better suited to the muddy, and probably somewhat deeper conditions in which Axelsro bioherms and biostromes formed. In this respect major Silurian reef builders were particularly well suited to growth in environments with relatively abundant fine sediment and this equipped them well for colonization of the soft, muddy, level bottom substrates which were widespread over the European craton during the Silurian.

Matrices and Cavities.—Mutual arrangement of the organic skeletons (e.g., the structure) in the reefs controlled the degree of volume occupied by loose bioclastic and argillaceous matrix and also the proportion of protected space which could remain unfilled as cavity. In these Silurian reefs the matrix is usually fine and argillaceous, often being a greenish micrite, and the cavity space is slight. Large open spaces in the Axelsro type reefs of Wenlock Edge tended to be infilled penecontemporaneously with reef growth (Scoffin, 1972, p. 566) despite the effect of non-skeletal stromatolites in converting an essentially dense structure into a frame. Of the original cavities only small ones, usually less than 1–2 centimeters in size, between or within skeletons escaped fill (Scoffin, 1972). This applies also even in the tighter frames of the Kuppen and Holmhällar reefs where fines, pumped or settling through the structure, show draped infilling of spaces. The filtering effect of these frameworks is reflected by the absence of coarse material near the centers of the reefs. In more open structures the matrix is less well sorted and includes admixtures of recognizable skeletal debris; mainly crinoid, brachiopod, ostracode and trilobite fragments.

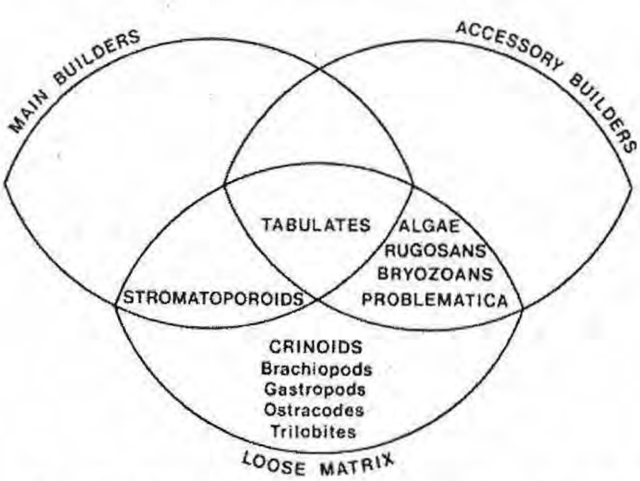

FIG. 53.—Principal sedimentological roles of calcified organisms in Silurian reefs.

Structure and Sedimentological Roles

Stromatoporoids and tabulates were the *main* reef builders; *accessory* builders either were attached to these large skeletons (e.g., calcareous algae, bryozoans, *Rothpletzella*, *Wetheredella*, ?spirorbids), or grew near them (e.g., rugosans); and all these organisms, together with those which spontaneously fragmented after death (crinoids, brachiopods), or which were free living (gastropods, *etc.*), added loose *matrix* which filled hollows of flanked skeletons (Fig. 53). Boring organisms are present in Silurian main reef builders (Stel, 1978a), but they do not appear to have substantially modified the strength of skeletons.

The Silurian reefs of northern Europe may show examples of all the main structural reef types which stromatoporoids were capable of producing. The irregular "ballstone" lenticles within Axelsro and Hoburgen reefs were produced by the amount of fine argillaceous matrix present and the fundamentally dense structure of these bioherms. They had important effects upon both the early and later stability of these accumulations (see Post-depositional Effects). They are absent in the tighter biostromes but what no stromatoporoid appears ever to have developed is an extensively branched form. Consequently, the cavernous frame structure of some scleractinian reefs is lacking in Middle Paleozoic reefs and the closest approach to a real framework is in the mutually encrusting, close packed, and varied morphotypes of the Kuppen biostrome and in the laminar frame of the Holmhällar type.

Calcareous algae, together with the problematic

Rothpletzella and *Wetheredella*, constitute the principal accessory encrusters of the reefs. Nonskeletal stromatolites had a similar role in binding and stabilizing the structure.

The coherence of a reef depends fundamentally upon its structure, which is determined by the shape and mutual arrangement of the component skeletons. Encrusting organisms certainly played a part in binding adjacent skeletons together in these reefs, but in most of the examples I have seen they have not been sufficiently abundant to override the effect of the shape of the *main* reef builders. Consequently structures dominated by domical and bulbous stromatoporoids, as is the case with parts of many Hoburgen reefs, were fundamentally unstable and were probably unable to raise themselves much above the local sea floor topography. Flatter skeletal forms were much more stable and the laminar frame Holmhällar reefs show hardly any disorientation of the constituent stromatoporoids.

It is not uncommon in European soft-rock circles to hear "off-the-cuff" remarks to the effect that "Silurian reefs are just debris piles." Overturned skeletons are, indeed, relatively common in Axelsro and Hoburgen reefs, but even in 1914 Crosfield and Johnston (p. 221) emphasized that the great majority of corals and stromatoporoids in the Wenlock Edge reefs are still in place. Since Silurian reefs of Europe range from dense argillaceous to frame structures it is not surprising that those at the "looser" end of this spectrum were susceptible to penecontemporaneous toppling of individual skeletons and local slumping of bioherm margins (see Post-depositional Effects). Local collapse of bioherm margins or toppling of vertically extended skeletons does not, in my view, constitute the difference between a reef and a pile of debris; as Scoffin (1971, p. 191) noted at Wenlock Edge "talus bands are rare," and this is my experience too.

A problem somewhat separate from the question of whether skeletons are in growth position concerns whether bioherms were skeletally constructed at all. In the first case a "bioherm" may be considered really to be a loose pile of moved skeletal material. In the second case, it may be found to lack skeletons altogether! This latter view has been argued for some of the Wenlock Edge bioherms by Abbott (1976). He considers that they lack an adequate skeletal framework and are really mud-banks localized and created through baffling of fine sediment by crinoids. The bioherm which he studied in detail is an Axelsro-type structure in Coates Quarry composed of micrite and *Halysites*. But this tabulate occupies only scattered parts of the bioherm and could only have influenced "a maximum of 23 percent of the structure. This, on its own, would have been inadequate to trap and stabilize the large quantities of lime mud . . ." (Abbott, 1976, p. 2123). Abbott's alternative explanation of crinoid baffling is stimulating, but it too seems to suffer from the same weakness for which *Halysites* is discarded, viz., there is relatively little crinoid debris in the mound. Abbott emphasizes the presence of crinoid material below and lateral to the mound but does not suggest that more than "scattered plates and columnals are present throughout the bioherms" (p. 2125). Bafflers need to be present in quantity to be effective and are very unlikely to be removed more easily from their habitat than the sediment they localize.

Seen in the perspective of the Silurian reef spectrum recognized here, the bioherm Abbott emphasizes is a sparse to dense *Halysites* structure. It is comparable with some Axelsro type reefs in Oslo and Gotland which do grade laterally into level bottom communities. Nevertheless, it does contain an unusually high proportion of micrite and its origin is not clear. But it is not valid to extend the uncertainty caused by this example to all Wenlock Edge bioherms since the majority, together with their counterparts in other areas, contain substantial proportions of tabulates and stromatoporoids. These do not usually contain the frameworks required by Abbott (1976; Abstract) to allow their comparison with "coral reefs," but they do normally possess a dense structure created by the close, in place growth of skeletized organisms.

Watkins (1979) also takes what may be termed an "understated" view of reef building by organisms in the Högklint bioherms near Visby. His detailed measurements are a valuable contribution to knowledge of Högklint reef composition, but it is possible to disagree with his interpretation of them. He (1979, p. 48) regards these Hoburgen type structures as mud-mounds on the grounds that micrite makes up "over half of the volume" (p. 41–42). So far as I know there is no formal definition of a carbonate mud-mound, but both ancient and modern examples have far higher proportions of mud than the 53 percent measured in these mounds. Watkins' (1979, fig. 7) counts show that stromatoporoids alone constitute approximately 15 percent of sediment volume in the bioherm sequence at Korpklint 1, with algae occupying at least a further 7 percent. Rugosans, tabulates and bryozoans are additional components and Watkins' own figures show that around one quarter of the bioherm is composed of skeletons which are in place or reef derived. But he concludes that "organisms did not actually *build* the Högklint bioherms in the area studied. Instead, they successfully exploited an environment of continually accumulating carbonate mud" (p. 42). I think that this exaggerates the importance

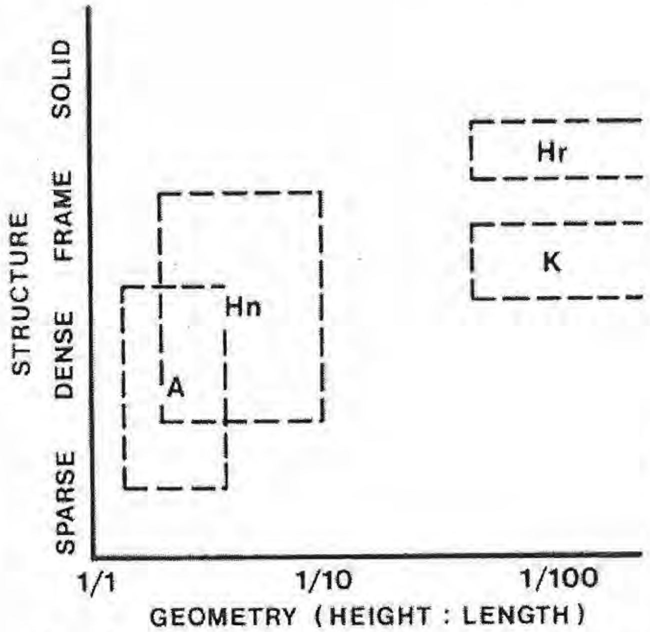

FIG. 54.—Relationship between structure and geometry in Axelsro (A), Hoburgen (Hn), Kuppen (K), and Holmhällar (Hr) bioherms and biostromes.

of physical sedimentation, and significantly underestimates the sedimentological role of the principal skeletal organisms.

Geometry

The tendency of Hoburgen reefs in shallowing-up sequences (e.g., the Högklint Beds) to flatten and coalesce upwards shows that bioherm and biostrome developments were not wholly separate, and an idealized shallowing sequence shows how these reef geometries may have been related (Fig. 48). Nevertheless, there appears to be a clear distribution between Axelsro-Hoburgen bioherms and Kuppen-Holmhällar biostromes based on presently available exposures both in terms of geometry and structure (Fig. 54). Axelsro and Hoburgen bioherms are irregularly lensoid in cross-section. This becomes converted into an inverted hat-shape where the Hoburgen reefs grade upwards into extended biostromal units (Fig. 55). The basal parts of the bioherms were often rounded in plan view. This is clearly demonstrated by the Hoburgen "*Philip structures*" impressed into the Visby Beds of Gotland's northwest coast (Fig. 33) which are sometimes virtually circular. Oval plans are shown by the Axelsro bioherms of Wenlock Edge (Scoffin, 1971, p. 186).

The biostromes are all very thin bodies with height-length ratios normally exceeding 1:100. Their plan views are uncertain, but may have been irregularly linear. Extremely shallow water is inferred to have been a major control on their overall geometry and their thinness has been enhanced by early post-depositional erosion in littoral-subaerial environments which resulted in bevelling, channelling and crevice formation on their upper surfaces, which are well seen at the Kuppen and Holmhällar localities themselves.

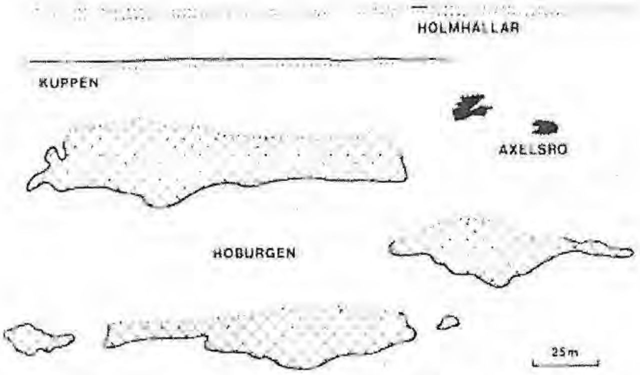

FIG. 55.—Relative cross-sectional shapes and sizes of Silurian reef types; dotted lines indicate erosion or cover.

The original local vertical relief of some of the bioherms may have been of the order of 7–10 meters (Nigel Watts, pers. comm., 1979). Kuppen and Holmhällar biostromes probably had the coherence to attain even greater relief, but whether they did is not yet known.

Post-depositional Effects

Paucity of accessory binding organisms, vertically extended domical or bulbous skeletons, and soft argillaceous substrates, combined in some Hoburgen bioherms, especially those with a dense non-frame structure, to make them inherently unstable. In contrast, Kuppen and Holmhällar frame biostromes appear to have been rigid structures and show no collapse features. These tendencies toward instability or rigidity developed as reef growth progressed and they conditioned later internal responses of the structures to compactional effects. Hoburgen and Axelsro reefs show relative movement of masses within individual bioherms because these sub-units are bounded partly or completely by argillaceous seams which facilitate sliding. The existence of semi-discrete rounded clay-bounded masses within these bioherms is one of the essential features of their structure, and was described early on as "ballstone." It led to incoherence within the reefs which generated lateral spalling (Fig. 56), and which also responded to subsequent overburden by differential movement (Watkins, 1979, p. 36). The relatively rigid frame biostromes took up compaction by intense stylolitization of adjacent skeletons.

Two factors which generate instability in Recent scleractinian reefs, however, were only of minor importance in the Silurian reefs. These are boring of skeletons by organisms and the presence of steep slopes in the reef environments.

TABLE 3.—SEQUENCE OF MEGASCOPIC STRUCTURAL MODIFICATION EFFECTS IN AXELSRO-HOBURGEN BIOHERMS

Syn-depositional		Post-depositional	
Early	Late	Early	Late
lateral spalling ⟶			
	⟵ internal fracture and rotation ⟶		
	⟵ sediment injection at base ⟶		
	compaction of underlying sediment ("*Philip structure*") ⟶		
			compaction of ⟶ overlying sediment ("*Cumings structure*")

The sequence of development of megascopic structural displacement features in and around Axelsro-Hoburgen bioherms changes from early collapse of reef margins to internal fracture and rotation of masses as the weight of the overlying reef increases (Table 3). The latter effect initiates sub-reef compaction which generates sediment injection. Both compaction and internal movement are increased by subsequent overburden. Consequently, early post-depositional features are principally internal squeezing and rotation of "ballstone" masses and marginal collapse, which give way progressively to external differential compaction effects on the surrounding sediments which create "*Philip*" and "*Cumings structures*." In contrast, Kuppen and Holmhällar biostromes appear to have been much more resistant to internal deformation due to their rigidity, engendered by a frame-solid structure. But they do show intense internal stylolitization effects, particularly in the Kuppen reefs. Effects on the sediment adajcent to these biostromes are difficult to assess due to lack of exposures.

Apart from Scoffin's (1972) study of cavities in Wenlock Edge bioherms, little work has yet been published on the diagenetic history of Silurian reefs in Europe.

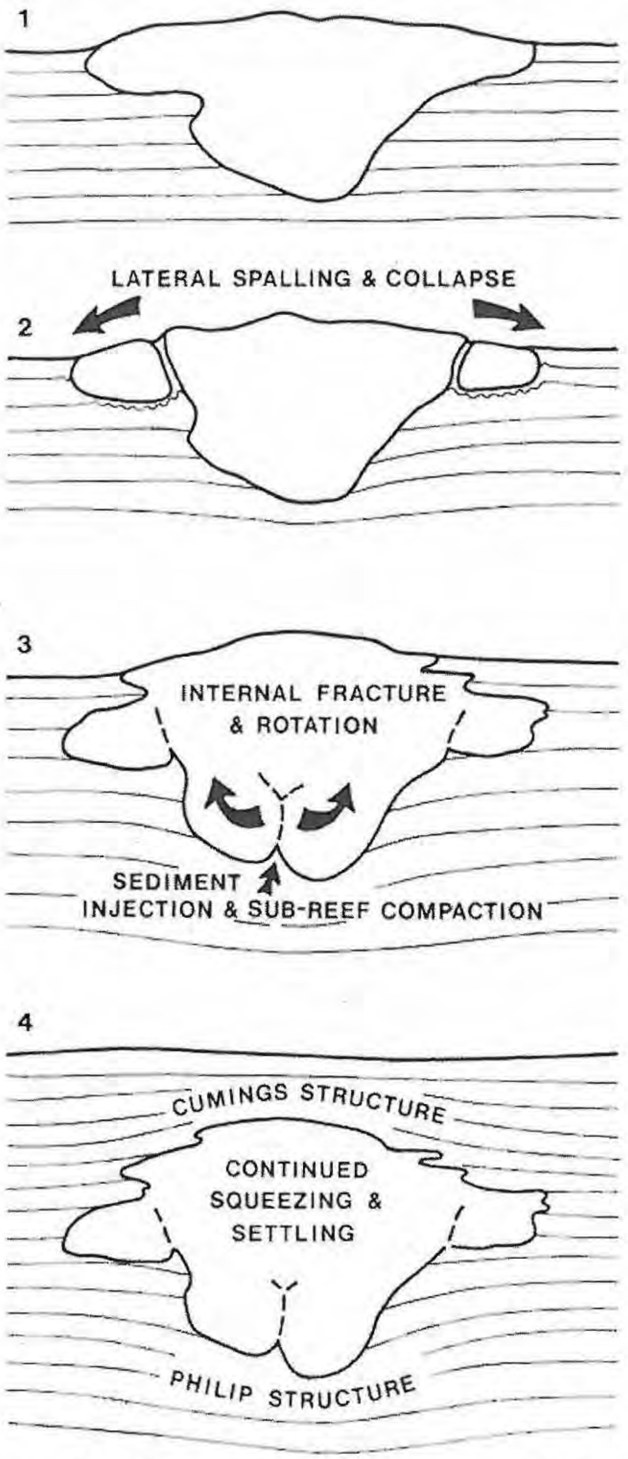

FIG. 56.—Stages in the evolution of megascopic displacement features of Axelsro-Hoburgen bioherms caused by penecontemporaneous and early postdepositional differential movement and compaction. 1. and 2. early stages of deposition; 3. late depositional stage; 4. early postdepositional stage. "*Cumings*" and "*Philip structures*" are compactional anticlines and synclines respectively; also see Table 3.

CONCLUSIONS

The principal reef building organisms during the Silurian in the northern European area were stromatoporoids and tabulate corals with locally significant contributions by rugose corals, calcareous algae, bryozoans and non-skeletal stromatolites. The majority of the reefs were bioherms formed by a mixed assemblage of these organisms and associated with a variety of surrounding sediments, from calcareous shales and argillaceous limestones to coarse bioclastic grainstones, the latter being a preferred substrate. The internal structure is characteristically a dense to frame accumulation with sub-units outlined by thin shaly layers which impart a general weakness reflected by settling, slumping and differential movement of parts of the bioherms. In Gotland, reefs of these types include the Axelsro and Hoburgen bioherms and this recognition of distinctive varieties of reef can be extended to other areas. The Wenlock Edge reefs, for example, are of Axelsro type as are the Fronian bioherms at Ringerike and Baerum in the Oslo Region. Biostromes are usually less diverse in composition and structure. Relatively quiet water biostromes dominated by tabulates occur in the Steinsfjord Formation (Stage 9c) of the southern Oslo Region and also in the Upper Visby Beds of Gotland at Irevik. Stromatoporoid biostromes representing shallow turbulent environments include the Kuppen and Holmhällar types of Gotland. These may represent fringing-reefs and contrast with the patch-reef developments of Hoburgen type on Gotland which are associated with extensive inter-reef sediments, as for example in the Högklint Beds.

Regional variation in reef development is correlated with position relative to the Caledonian mobile belt and to the craton interior. Reef development appears to have been limited in the Welsh Borderland by fine siliciclastic sedimentation and by the relatively deep water situation. Reefs only occur in the late Wenlock during a temporary shallowing of the sea and reduction of siliciclastic sediment influx. They are of Axelsro type which can be regarded as the deepest of the main reef types.

In the Oslo Region reefs also show signs of the controlling effect of broad sedimentational patterns: bioherms and biostromes are restricted to the upper Llandovery and Wenlock and all show variations on the basic Axelsro type, e.g., they are dominated by tabulate corals and *Rothpletzella-Wetheredella* crusts, and are generally enclosed by relatively fine-grained sediments.

The Gotland sequence is both the thinnest and the most carbonate-rich of the four sequences, and it also contains the most extensive and diverse reef developments. Four distinctive reef types can be recognized: Axelsro, Hoburgen, Kuppen, and Holmhällar, which broadly represent a trend from deeper, tabulate dominated bioherms with a relatively weak internal structure to shallow, stromatoporoid dominated biostromes with a strong rigid framework. Reefs range in age from upper Llandovery to upper Ludlow and can be related to a gross sedimentational pattern of interdigitating carbonate and shale wedges which represent shallowing-up (regressive) and deepening-up (transgressive) phases.

The Estonian sequence is comparable with that in Gotland but the reefs, which also occur at several horizons, are less well documented.

The Axelsro-Hoburgen-Kuppen-Holmhällar range of reef types exhibits contrasting geometric, compositional and structural features which are controlled by environmental factors, on the one hand, and which largely determine their physical stability and responses to post-depositional effects on the other (Table 2). Restriction of the full spectrum of types to the Baltic area reflects the importance of regional controls on reef development and it makes Gotland the prime location for studying the range of in place skeletal accumulations formed in the European area during the Silurian. These reef structures were constructed mainly by stromatoporoids and tabulate corals, and the environmental requirements, growth rates and morphologies of these still problematic organisms determined their essential features.

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