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CORAL REEFS OF BALTIC SILURIAN (STRUCTURE, FACIES RELATIONS)

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According to recent ideas the Baltic Silurian basin was a typical Early Paleozoic pericontinental sea. At the time of its maximum distribution the sea cut deep into the peneplaned Fenno-Sarmatian continent. As a result of the continental uplift the sea gradually retreated to the south-west, towards the Central-European Hercynian Geosynclinal Basin (Walter, 1972; Нестор, Эйнасто, 1977; Кальо, Юргенсон, 1977). Representing a near-equatorial shallow platform-sea, the Baltic Silurian basin offered favourable conditions for the development of tabulate corals, stromatoporoids, rugose corals, bryozoans and calcareous algae capable of constructing the frame of various organic buildups: bioherms, biostromes, banks, and more seldom small bioherm complexes, further conditionally called reefs. These buildups are mostly unstratified small bodies 3-5 m, rarely 10 m high, some tens of metres across and are enclosed in well-bedded biodetritic, biomorphous and pelletal limestones poor in terrigenous admixture. They are less numerous in nodular muddy bioclastic limestones. These relations show a comparatively wide facial range of the development of organic buildups: from shoal barriers (overwhelming majority of buildups) to extensive open shelf, incl. (in press). Thus, shoal and shelf reefs can be distinguished in the Baltic Silurian basin. Applying facial analysis it was established that shoal sedimentary barriers with reefs developed in the highest energy wave activity zone. Being narrow (to 10 km) they ran many hundred kilometres. In addition to characteristic carbonate sediments the formation of chains of different organic buildups resembling modern reef barriers evidently took place just in this part of the basin. However, genetically authentic barrier reefs did not exist here. Unlike, e.g. the Great Barrier Reef of Australia running along the steep outer margin of the Coral Sea shelf, most of the Paleobaltic Silurian organic buildups developed within the stable shelf basin at the gentle slope of the sea bottom. Thereby, they resemble the patch reefs particularly numerous in the wide southern part of the eastern shelf of Australia between the continent and the Great Barrier Reef.

At times, the Silurian shoal barriers and associated organic buildups were very extensive (Fig. 1). E.g., the Wenlock and Middle Ludlow bioherms form distinct shoal barriers from Gotland through Saaremaa and the southern Baltic to Volyno-Podolia, i.e. within a distance of approx. 1,500 km (Эйнасто и др., 1980). During recurrent transgressions and regressions the shoal barriers removed considerably. The most favourable conditions for the formation of organic buildups existed at the regressive phases of the basin development. This is evidenced by the regular position of the shoal reefs in sedimentary cycles: the reefs are underlain by nodular open-shelf limestones and overlain by lagoonal primary dolomites (see Nestor, Einasto in this book, Fig. 2).

Middle Wenlock and Middle Ludlow were the epochs of the maximum reef development. In between these epochs the shoal facies belt, most suitable for the reef formation, migrated in the East Baltic for a distance of 300 km but on Gotland and in Podolia only for 15-40 km. Supposedly, this difference indicated the presence of a much steeper continental slope in the latter.

Further from the shoal barrier towards the outer shelf edge the shelf reefs were located. More precisely, they occupied the central part of the shelf, and probably its

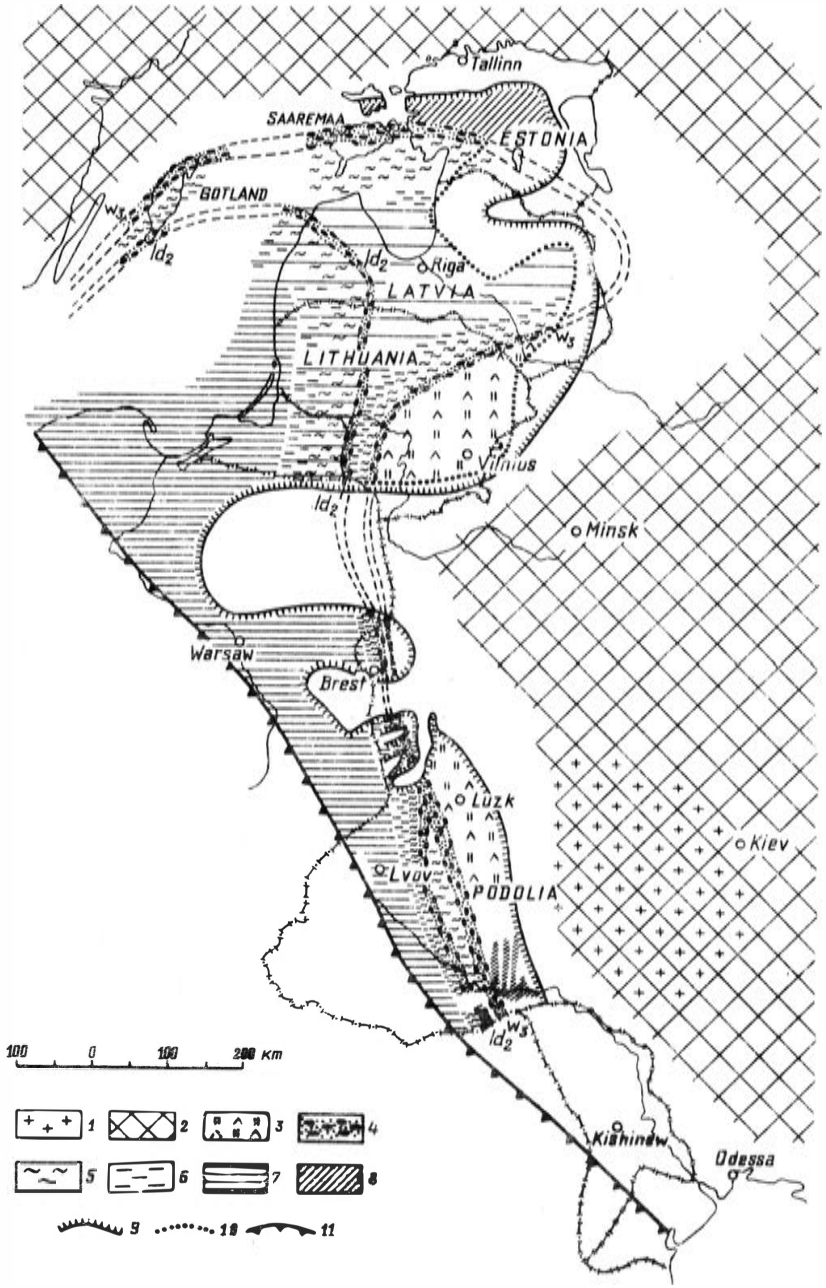

Fig. 1. The Wenlock (w_3) and Middle Ludlow (ld_2) bioherms form distinct shoal barriers from Gotland to Volyno-Podolia (from Эйнасто и др., 1980).
1 - Ukrainian Shield, 2 - Fenno-Sarmatian continent, 3 - lagoonal dolomites and gypsum, 4 - calcarenites and organic buildups of the shoal facies belt, 5 - nodular limestones of the open shelf belt, 6 - marls of the slope belt, 7 - graptolite mudstones and shales, 8 - outcrop area of the Silurian rocks, 9 - limit of the present distribution of Silurian rocks, 10 - contour of complete thickness of Jaagarahu Beds (Wenlock), 11 - Törnquist Line.

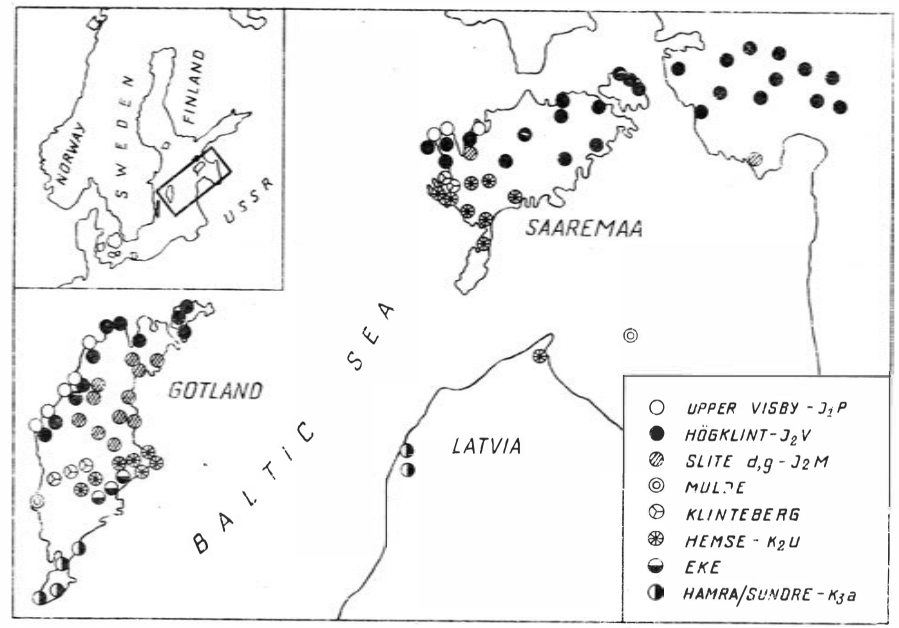

Fig. 2. Distribution of the Silurian organic buildups in Gotland and East Baltic.
Explanation of stratigraphical indexes - see table in Preface. The distance between Gotland and East Baltic is reduced.

elevated portions (dome or bar-shaped structures). The shelf reefs were small bodies (biostromes, bioherms) varying from some metres to some tens of metres in diameter, and consisting mainly of dendroid or bush-shaped tabulates. Stromatoporoids were rare. These organic buildups are most similar to the modern patch-reefs.

These are general considerations of the reef development in the Silurian Paleobaltic basin. Further, we shall present more specific data by analysing the Wenlock and Ludlow on Gotland and in the East Baltic from the comparative aspect.

The earliest Wenlock reefs on Gotland are known from the Upper Visby Marls (Fig. 2), formed in the inner area of the open shelf. They are small buildups of knoll, cone or lens - shaped composed chiefly of tabulate corals (halysitids, favositids) and heliolitids, i.e. of an assemblage characterized by a higher tolerance to muddy substrate (Manten, 1971; Stel, 1978). The maximum height of the buildups is 3.5 m but frequently they are much smaller. V. Jaanusson (1979) having studied them in detail called these unstratified bodies knolls and mounds. He supposed that on forming they rised only slightly from the sea bottom. By our identifications in these buildups predominates favositid *Angopora hisingeri* associated with *Planalveolites foughti*, *Heliolites decipiens*, *Stelliporella* sp., rare *Catenipora* and fairly small stromatoporoid coenostea. The skeletons of the associated species did not constitute more than 10-15 % of the volume of buildups.

Buildups of the same habit, structure and analogous facies relations have been established in the nodular clayey limestones of the Jaani Stage (the Paramaja Formation) at the base of the Silurian cliff on Saaremaa (Fig. 2).

On Gotland the Early Silurian reef development culminated in Högklint time. Huge algal-stromatoporoid-coral buildups up to 20 m high and several hundred metres long often take their beginning from the very base of the Högklint Beds. They are well exposed in the NW cliffs of Gotland and thoroughly studied by many authors (Hadding, 1950; Rutten, 1958; Manten, 1971; Eriksson, Laufeld, 1978; Stel, 1978, etc.). By K. Mori (1968) the main reefbuilder was the stromatoporoid *Vikingia tenue*, in the inter-reef areas dominated *Densastroma pexisum* and *Simplexodictyon simplex*. Of tabulates *Favosites mirandus* is associated with reefs. C.-O. Eriksson and S. Laufeld (1978) have demonstrated that the Högklint reefs occupied a belt 10 km wide and almost parallel to shore line.

An analogous reef assemblage is known from the East Baltic (Fig. 2). However, in this region it appears somewhat later in comparison with Gotland. In the Ninase Member of the Jaani Stage (Клааманн, 1977) the equivalent of Högklint "a" with reefs of *Vikingia* is lacking. Instead of them there occur small bryozoan bioherms (1-2 m in diameter). Stromatoporoid reefs are also absent in the overlying part of the Jaani Stage. *Vikingia* reefs appear in the basal portion of the Jaagarahu Stage, in the Vilsandi Beds. Jaagarahu reefs are huge: 10-16 m high and several km across (Аалоэ, 1970). The main reefbuilders are *Vikingia tenue* and stromatolites; *Favosites mirandus*, *Coenites juniperinus* and colonial rugose coral *Acervularia ananas* are rarer. The Early Jaagarahu reefs form a long chain running through the whole northern part of Saaremaa, and continuing in the mainland of Estonia and to the SSW of it. Borings have shown that the reefs represent a belt at least 10 km in width. Unfortunately, most of the organic buildups in the territory of Estonia are heavily dolomitized and, therefore it is hardly possible to identify the reef-forming organisms even on the group level. It seems that to the east of the western coast of Saaremaa the role of the calcareous algae, halysitids and solitary rugose corals increases and that of *Vikingia tenue* decreases.

By lithological characters (see Jaanusson, 1979) the deposits enclosing Högklint bioherms are mainly sparite limestones; so, they may be considered according to the facies model of the basin (Нестор, Эйнасто, 1977) as belonging to the shoal belt. To

this conclusion seems to contradict the presence in Högklint reefs of *Dicoelosia verneuliana* which has been taken as an indicator of the quiet-water environment in Wales and Welsh Borderland (Hurst, 1975). One can evidently agree with J. Stel (1978) who pointed out that not all *Dicoelosia*-species had the same facies range. However, the absence of *D. vernuiliana* in *tenue*-reefs of the East Baltic may indicate that these buildups, occupying somewhat higher stratigraphical position, were perhaps located closer to the shore than the reefs of analogous species content on Gotland.

The next reef level well defined in the whole northern part of the Silurian Baltic basin occurs on Gotland in the Slite Beds, particularly in Slite "d" and "g", and on Saaremaa in the Maasi Beds of the Jaagarahu Stage (Fig. 2). By their shape these buildups may be called biostromes. They are flat bodies full of halysitids, teciids, favositids, auloporids and rugose corals. Stromatoporoids are of secondary significance. In the coral assemblage *Halysites junior* and *Thecia confluens* predominate but dendroid *Barrandeolites bowerbanki, Palaeofavosites collatatus, Pf. tersus, Subalveolites sokolovi, Heliolites decipiens, Aulopora enodis,* tetracoral *Microplasma schmidti,* etc. are also numerous. Large bioherms with *Halysites junior* are developed only in the very south-western part of the region (Stora Kalsö Island). As to their facies position the *junior-confluens*-reefs are shoal ones. Upwards of the Slite Beds in the Wenlock of Gotland the organic buildups of three stratigraphical levels are known to us. These come from (1) Halla "b", (2) the Mulde Beds, and (3) the middle of the Klinteberg Beds (Fig. 2).

Common features for these buildups are: small size, peculiar species content, and the absence of direct analogs of them in the Wenlock of the East Baltic. Halla bioherms (Hörsne outcrop) differ from the others in large number of small dendroid and encrusting tabulates and bryozoans: *Parastriatopora priva, Thecia expatiata, Coenites juniperinus, Palaeofavosites asper, Desmidopora acuminata,* etc. Judging by the first three species, these buildups may be situated on the level of the uppermost part of the Maasi Beds in the East Baltic. Taking into account the small size of Halla coelenterates and bryozoans, the morphology of their colonies, and analogous position in modern reefs of similar adaptions, it can be supposed that the bioherms built by above-mentioned organisms were located in the onshore side of shoal barrier or in the outshore of a lagoon (Клааманн, 1982).

From the Mulde Beds only one organic buildup (Blåhäll outcrop) is known. It is a thin (0.25 m) biostrome consisting of dendroid proporids (heliolitids), not identified on species level so far. It is enclosed in monotonous mudstone full of unjoined meshes of halysitids (*Halysites laticatenatus*) and hemispheric colonies of *Favosites gothlandicus*. The enclosing rock seems to suggest this biostrome as the most open sea buildup in the Baltic Silurian, formed at the outer margin of the open shelf.

The bioherms of shoal facies belt occur at Klinte and Hunninge (the Klinteberg Beds). Of the reefbuilders dominate *Halysites klintebergensis* and *Palaeofavosites tersus*, partly also thin dendroid corals and bryozoans, closely resembling those in the bioherms of the Halla Beds at Hörsne.

The second maximum of reefbuilding in the Baltic Silurian basin took place in the Ludlow, particularly in Hemse and Paadla times when bioherms and biostromes were equally well developed on Gotland and in the East Baltic. However, the reefs of these regions reveal some differences. E.g., on Gotland the bioherms analogous to those of Early Paadla time, and consisting of *Thecia swindereniana, Subalveolites, Densastroma podolicum* and a rich assemblage of other stromatoporoids, are not established. But almost identical are the assemblages of reef-forming coelenterates in the Uduvere Beds and those of the Hemse Beds on the Östergarn Peninsula and in Linde area. In this assemblage predominate massive or encrusting stromatoporoids (*Plectostroma*-species,

Syringostromella borealis, *Lophiostroma*, etc.). Between them occur gatherings of cylindric tabulates *Laceripora cribrosa* and *Parastriatopora coreaniformis* and bushes of syringoporids. If in the East Baltic the buildups of this content are represented by thin (approx. 1 m high) biostromes, those on Gotland reach the thickness of 4-5 m. Being enclosed in well-bedded limestones these biostromes might possibly develop in shoal environment.

The organic buildups in the Eke Beds of Gotland are known to us from the localities surrounding Laubackar (Hallsarve, Källstäde, Botvide). The moundlike bodies consist of marls and contain numerous small mushroom shaped or encrusting colonies of alveolitids and heliolitids. Stromatoporoids are of secondary significance. The facies position of Eke reef in unclear. Abundant encrusting alveolitids which in the East Baltic Silurian are mostly connected with lagoonal facies belt call for location of these buildups in the near-shore though quietwater part of sea (onshore side of shoal barrier?).

On Gotland the uppermost Silurian is represented by the Hamra and Sundre Beds which are also rich in buildups (Fig. 2). The number of reefbuilding species is limited but the individuals are numerous. Most important are stromatoporoids among which encrusting coenostea dominate (*Plectostroma scaniense*, *Parallelostroma typicum*, *Lophiostroma schmidti*). Tabulate corals *"Palaeofavosites" moribundus*, *Favosites similis*, alveolitids and syringoporids are of note. All of these coelenterates are known in the Silurian of Gotland from the Eke Beds and overlying ones. In Estonia this kind of bioherms is not known though the majority of species are frequent in the uppermost part of the Paadla Stage and above it. But in West Latvia the buildups of almost identical species content have been discovered by boring (Ventspils core). These buildups are the youngest by their age in the East Baltic Silurian (Ventspils Formation, the topmost Ludlow). Evidently, in the northern Baltic the regression of the sea at the end of the Ludlow (in Kuressaare time) was so rapid that the most favourable conditions for reef building occurred already southwards the territory of Estonia.

In conclusion it can be said that during the whole Wenlock and Ludlow reefs were characteristic of the northern part of the Paleobaltic. They are especially abundant on Gotland where at least 9 levels with reefs of different age have been preserved. Suggesting general regression of the basin, they replaced regularly each other towards the south and south-west. The coincidence of the succession on Gotland and in Estonia shows the presence of reef belts situated roughly parallel to the shore line. This succession was partly interrupted at the end of the Wenlock at the time of Silurian maximum regression (in Rootsiküla time) when reef formation took place only on Gotland (evidenced by buildups in the uppermost Halla Beds, the Mulde and Klinteberg Beds).

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КОРАЛЛОВЫЕ РИФЫ В СИЛУРИЙСКОМ БАССЕЙНЕ БАЛТИКИ /СТРОЕНИЕ, ФАЦИАЛЬНАЯ ПРИУРОЧЕННОСТЬ/

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Органогенные постройки /биогермы, биостромы - условно названные как рифы/ приурочены в силуре Балтоскандии к двум фациальным зонам: 1/ к подвижноводной отмельной зоне /преобладающее большинство/ и 2/ к открытому шельфу.

Отмельная зона представлена детритовыми криноидными и ракушечно-детритовыми известняками, с которыми ассоциируются кораллово-строматопоровые биогермы. Внутренняя сторона зоны, в основном с водорослевыми биогермами, сложена илисто-детритовыми, битуминозными глинистыми известняками и мергелями, переходящими в сторону берега в однородные доломитовые мергели. Органогенные постройки отмели являются наиболее крупными в силуре Балтоскандии и отличаются заметно линеарным распространением /в частности биогермы слоев Хёгклинт и яагарахуского горизонта/ /рис. 1/.

Рифы открытого шельфа небольшие, напоминающие т.н. лоскутные рифы, бугры или возвышения дна современных морей. Они вероятно, лишь немного возвышались над дном силурийского моря. В разрезе подобные постройки заключены в комковатых известняках и мергелях. Сложены они плоскими колониями фавозитид, корковидными альвеолитидами, толстостенными хализитидами и кустистыми сирингопоридами /постройки Верхних мергелей Висбю, мергелей Хемсе, вентспилской свиты лудлова и др./.

В течение почти всего силурийского периода органические постройки были особенно полно представлены в северной части Палеобалтики - в частности в районе Готланда, где сохранились следы по меньшей мере восьми разновозрастных рифов /рис. 2/.

Биогермы и биостромы силура Балтоскандии формировались в регрессивных фазах развития бассейна. Максимумы рифообразования были в среднем венлоке и среднем лудлове. В течение этого интервала времени наиболее подходящая для рифостроителей отмельная зона мигрировала в пределах Прибалтики около 300 км, а на Готланде и в Подолии лишь 15-40 км /рис. 1/. Думается, что в двух последних регионах материковый склон был заметно более крутым и стабильным.