Stratigraphical and environmental background

VALDAR JAANUSSON

General stratigraphical relationships

The location of the Vattenfallet section is best described in Lindström's words (in Thorell & Lindström 1885:3): "Just beyond the mediaeval walls of the town of Visby, on its southern side, there is a public park extending along the shores of the Baltic. It is called "Palisaderna" (=the palisades) from some part of the fortifications of the now vanished castle of Visborg, which formerly stood close to this locality. A natural ravine, excavated by the action of water, traverses this park from east to west. It bears the name of Gammelå (=the old brook) or more commonly "Vattenfallet" (=the Waterfall)."

The rock exposed at Vattenfallet on the steep slopes of a series of diminutive canyons belongs to the uppermost Lower Visby Marl, the Upper Visby Marl and the Högklint Group as defined by Hede (1921). In descending order the section is briefly as follows (levels refer to height above sea-level).

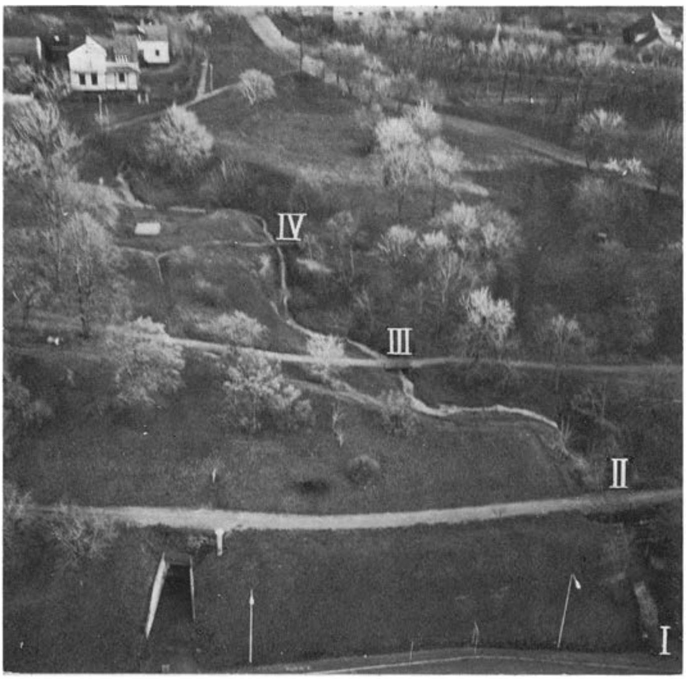

Fig. 1. Aerial photograph of the Vattenfallet area taken by Arne Philip in November, 1977. The numbers of bridges over the brook correspond to those in Fig. 2.

Högklint Limestone 20.0 m

29.6–30.0 m. Högklint *d* (so-called *Pterygotus* Beds). Soft pelletal marl and calcareous mudstone with some thin intercalations of pelletal limestone (for detailed section, see Hedström 1904 and below).
24.2–29.6 m. Högklint *c*. Regularly bedded limestones (sparitic pelletal calcisiltites to sparitic pelletiferous calcarenites) virtually without argillaceous intercalations. In the upper 80 cm the rock consists of sparitic calcirudites to conglomerate.
12.65–24.2 m. Högklint *b*. Somewhat nodular to regularly bedded limestones with argillaceous intercalations of varying thickness. In the lower 3.5 m the limestone consists predominantly of calcilutites; limestone beds of the remainder of the division are formed of micritic to sparitic pelletiferous calcarenites.
10.02–12.65 m. Högklint *a*. Thick-bedded, coarse-grained limestones (sparitic calcarenites) with thin argillaceous intercalations.

Upper Visby Marl 8.9 m

3.8–10.02 m. Irregularly bedded to nodular limestones with argillaceous intercalations of varying thickness. The composition of limestone beds varies from calcilutites to micritic and sparitic calcarenites.
1.1–3.8 m. Nodular to irregularly bedded argillaceous limestones with argillaceous intercalations that mostly exceed the thickness of the limestone beds. The limestone is mainly calcilutite.

Lower Visby Marl 0.7 m +

0.4–1.1 m. Lithologically indistinguishable from the lowermost Upper Visby Marl.

The boundary between the Lower and Upper Visby Marl cannot be defined lithologically but it is sharp faunally. The Lower Visby Marl is not easily accessible at Vattenfallet and the available small samples did not contain large

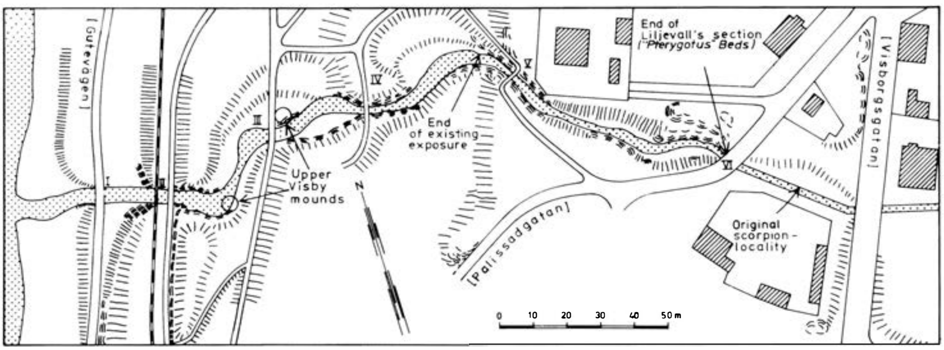

Fig. 2. A copy of Liljevall's map of the Vattenfallet area. The successive bridges over the brook are numbered. In order to facilitate orientation, the modern names of streets are given in brackets.

macrofossils. The boundary is particularly well defined by palaeocope ostracodes, not only qualitatively (Fig. 41) but also quantitatively (Fig. 44). Among small macro-organisms the brachiopod *Eoplectodonta transversalis* and the tentaculitoid *Gotlandellites visbyensis* have never been found above the Lower Visby Marl. Every sample from the Lower Visby Marl also contained several specimens of the distinctive rugose coral *Palaeocyclus porpita,* which is common on Gotland only in this topoformation, although it also occurs rarely in the Upper Visby Marl (Lindström 1861:340; Mori 1969:20; Sheehan 1977).

The top of the section has been assumed to correspond to the boundary between the Högklint and Tofta Limestones. However, Liljevall's observations indicate that the main break in the sequence is at the base and not at the top of the "*Pterygotus*" Beds. Because of the lack of existing continuous exposures in this part of the sequence in the Vattenfallet area, the stratigraphical significance of the break is difficult to determine. The overlying beds (31.0–31.8 m), which are discontinuously exposed, contain oncolites ("*Spongiostroma*") and lithologically resemble parts of the Tofta Limestone.

The index letters for the lithostratigraphical subdivisions of the Högklint Limestone are here used in the same sense as by Laufeld (1974a:8). The boundaries of the subdivisions are not necessarily synchronous over the whole outcrop area in which these lithological units can be distinguished.

Several authors have suggested that the Tofta Limestone is only a facies of the upper part of the Högklint Limestone (Hadding 1956; Jux 1957; Mori 1969; Manten 1971), but from a stratonomic point of view this is hardly possible. In places where the contact relationships between the Högklint reefs and the Tofta Limestone can be observed or deduced the oncolitic ("*Spongiostroma*") Tofta Beds always overlie the Högklint reefs (Martinsson 1967:362). If the Högklint reef mounds continued to grow during deposition of the Tofta Beds, this must have taken place outside the present outcrop area.

For stratigraphical orientation along the brook the following notes may be useful. The stream is crossed by a number of bridges, numbered originally by Liljevall in ascending order from I to VI (Figs. 1,2). The first bridge (Fig. 3) has now been replaced by the broad road, named Gutevägen, alongside the harbour, so from that point to the west the brook runs underground to the sea. Immediately east of Gutevägen is the first waterfall and a canyon cut into the lower part of the Upper Visby Marl (Fig. 3). East of the second bridge is the second waterfall (Hedström 1910, Fig. 60b; 1912, Fig. 10), where the top of the section is formed by thick-bedded limestones of Högklint *a,* the base of which (10.02 m) forms one of the easily recognizable index horizons in the section. Below the fourth bridge is the third waterfall (Hedström 1910, Fig. 60a; 1912, Fig. 11) with a canyon cut into the limestones of Högklint *b*. The thick bentonitic bed (17.0 m) close to the summit of the waterfall is a further

Fig. 3. Vattenfallet, photograph of the first bridge (now Gutevägen) from the west, with the second bridge in the background. In the left background the steep wall is formed by the lower part of the Upper Visby Marl (about 3–6 m above sea-level). Photograph by K.J.A. Gardsten, probably around 1900; by courtesy of the Gotland Museum, Visby.

important index horizon. The existing exposure, still in Högklint *b*, extends eastwards almost to the point where, in Liljevall's time, the fifth bridge crossed the brook. Southeast of that point the brook now runs underground in a drain and bedrock is no longer exposed. The nearest outcrop of Högklint *c* is a low road-cut (with a section of c. 0.5 m) at Palisadvägen, about 50 m southwest of the brook. Högklint *d* ("*Pterygotus*" Beds) was accessible to Liljevall just north of the sixth bridge at what now is Palisadgatan. Lindström's scorpion-locality was located 30 m farther southeast along the brook (Fig. 2). For the location of pegs used for topographic fixed points, see Laufeld (1974b, Fig. 26; note that in that figure the numbers of the scale should be reduced by a factor of ten).

A stratigraphical correlation of the Vattenfallet section with conodont and graptolite zonations is given in Table 1. For details see Jeppsson (this volume) and Skoglund (this volume).

The boundary between the Lower and Upper Visby Marls appears to correspond to the boundary between the Llandovery and Wenlock Series (Bassett & Cocks 1974:4–5). The Upper Visby Marl and Högklint Limestone belong to the lower part of the Sheinwoodian Stage.

Series	VATTENFALLET		Conodonts	Graptolites
Wenlock	Tofta		*Hindeodella sagitta*	?
	Högklint Limestone	d		
		c		
		b	*[Kockelella patula]*	*Monograptus riccartonensis*
		a		*[Cyrtograptus murchisoni]*
	Upper Visby Marl			*[Cyrtograptus centrifugus]*
			Pterospathodus amorphognathoides	
Llandovery	Lower Visby Marl			*[Monoclimacis crenulata]*

TABLE 1. Correlation of the Vattenfallet sequence with the graptolite and conodont zones.

General lithofacies relations

Much of present knowledge of the distribution of various Silurian lithofacies in the Balto–Scandian region is based on gross macroscopic characteristics and not on rock composition derived from quantitative data. For this reason definition of lithofacies belts is often vague, and the location of boundaries between the belts is uncertain in places.

The Upper Visby Marl belongs to a lithofacies belt in which the rock can be characterized as an alternation of thin beds or nodules of limestone and friable calcareous mudstone ("marl"). The limestone mostly has a high terrigenous clay content. For brevity, this belt is here termed the marl belt. It can be followed eastwards into the lower Jaani Marl of Saaremaa and the eastern mainland of Estonia (Kaljo 1970, Fig. 84; Kaljo & Jürgenson 1977, Fig. 4). Southwards the terrigenous clay content increases and the marl belt merges into a belt formed mainly of mudstone and shale. Whether the boundary between these belts is within southern Gotland or south of the island cannot be determined before cores have been studied lithologically. Northwards the marl belt was probably bordered by a belt consisting of bedded limestone in which argillaceous intercalations have a subordinate importance. There is a good possibility that this belt also included patches of reef-like stromatoporoid mounds. On the assumption that this belt did exist at all, it has now been completely removed by erosion.

Distribution of the main lithofacies belts during the period of deposition of the Högklint Beds is shown in Fig. 4. During this time skeletal sand, pelletal silt, and argillaceous carbonate mud was deposited on northwestern Gotland, now forming various bedded limestones of the outcrop area. Rock with a similar lithology probably extends also east of northern Gotland below the sea-floor. This is all that remains of a lithofacies belt which possibly extended along much of the northern margin of the Balto-Scandian epicontinental basin. In Estonia rocks of Högklint age (represented by a part of the Jaani Stage) are formed of marlstones belonging to the marl belt (Kaljo 1970, Fig. 84). The bedded Högklint limestones of northwestern Gotland merge to the south and southwest into similar marl deposits, but details are unclear. The mudstone and shale belt is located farther to the south and southwest.

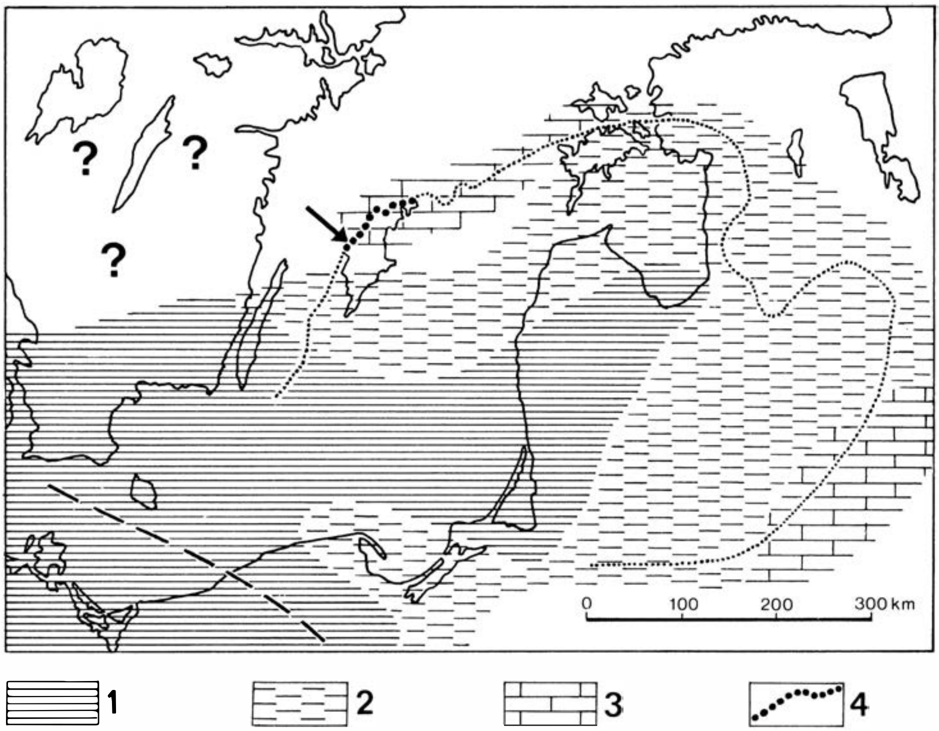

Fig. 4. Distribution of the main lithofacies in southern Balto-Scandia during early Wenlockian times when the Högklint Limestone was deposited. East Baltic area after Kaljo & Jürgenson (1977, Fig. 4); various highly argillaceous limestones with mostly friable "marly" intercalations are grouped together as "marl". Dotted line, the boundary of the preserved subsurface and submarine Wenlockian deposits of the Russian Platform, including the outcrop areas; thick dashed line, the approximate boundary between the epicontinental sea of the Russian Platform and the Wendean Basin. The position of the Vattenfallet area is indicated by an arrow. 1, shale and mudstone; 2, "marl"; 3, bedded, predominantly calcarenitic limestones; 4, reefs of the outcrop area.

In its outcrop area the Högklint Limestone contains a great number of separate lenses of massive limestone of varying size (Eriksson & Laufeld 1978, Figs. 4–6), some up to two kilometres in cross-section and up to 30 m thick. These unstratified, mainly flat lenses abound in stromatoporoids and are generally regarded as representing a type of reef with accompanying flank deposits (Hede 1933, 1940; Hadding 1941, 1950; Rutten 1958; Manten 1962, 1971). Despite of numerous studies, the construction of the reef-like mounds still is poorly understood. The distribution of the reefs along the outcrop area gives the impression that they form a well-defined individual belt, which has been compared with a barrier reef (Wedekind & Tripp 1930; Jux 1957). However, the original spatial extent of the Högklint reefs is difficult to reconstruct and they may well have been developed also to the north of the outcrop area, where the equivalent sequence is now eroded away. That they had been developed immediately outside the present coast has been inferred from the distribution of so-called Philip structures (Eriksson & Laufeld 1978). The outcrop area of the reef belt appears to be at least slightly oblique to the original axis of the belt (see also Fig. 4), and may represent the southern margin of an originally wide belt with numerous patch reefs. In any case, the comparison with a modern ocean-facing barrier reef is misleading in several respects.

The Vattenfallet section is in bedded limestones between the reefs, and to understand depositional conditions it is important to know how much the reefs controlled sedimentation around them. In this respect widely divergent opinions have been expressed. According to Jux (1957) much of the coarse-grained bedded limestone sequence on Gotland consists of material derived from the reefs. On the other hand, Rutten (1958) found almost no influence of the Högklint reefs on sedimentation in the immediate reef-surroundings. Manten (1971:217–219) traced the distribution of reef-derived debris and found that even within a relatively short distance from the reef the proportion of coarse reef debris in the sediment is fairly low.

The sediment now forming bedded limestones around the reefs was deposited at almost the same rate as the reefs (Hadding 1941, 1950). According to Hadding (1941) the surface of a reef cannot have protruded more than a few metres above the level surface of the surrounding sea-floor. Thus during the growth of a reef, its surface formed a low mound of varying dimensions, normally flanked by a belt of reef talus mixed with autochthonous skeletal remains. Only a short distance from a reef, pelletal silt and skeletal sand was deposited. Pellets could not possibly have been derived from the reef. The relative importance of reef-derived skeletal material in the inter-reef deposits varied with the distance from, and the size of the reef and is now difficult to estimate. However, the general impression is that, in terms of the source of sedimentary particles, the reefs seem to have exerted only a limited control on sedimentation between reefs. The sea-floor between reefs supported a varied fauna and flora which probably produced much of the carbonate sediment in that environment.

Limestone lithologies

Remarks on methodology and terminology

The principal method of quantitatively studying microlithology of the limestone is point counting of thin sections. Application of this method to limestones has been discussed recently by Jaanusson (1972) and the recommendations outlined there are followed here. The main pertinent points are as follows. (1) Skeletal sand is defined as those skeletal particles of 0.1 mm or greater length in thin section (Jaanusson 1952; Martna 1955). (2) Sparry calcite comprises inter- and intragranular cement, rim cement, and frequently also some neomorphic calcite formed by assimilation (recrystallization) of skeletal grains and other carbonate particles into sparry calcite mosaic. (3) The matrix, that is most of the remainder of the rock, consists of material of various origins, such as skeletal grains smaller than 0.1 mm in thin section, carbonate mud, terrigenous mud, and considerable amounts of calcium carbonate cement incorporated into micrite. (4) The grain-solid definition of the skeletal grain (Dunham 1962) is applied.

Discrete micritic particles are here classified as peloids (McKee & Gutschick 1969). They mostly represent true indurated pellets, but also include completely micritized skeletal grains, fragments of such grains or of micritic envelopes, and micritic envelopes cut by the thin section so that skeletal core is not visible. The predominant size range of peloids in the Vattenfallet section is between 0.03 and 0.07 mm, but some attain larger size, particularly in beds in which micritic envelopes are abundant. In order to show the importance of peloids as a constituent of the rock, it is advantageous to distinguish here between peloids and the matrix proper. As the true indurated pellets represent the majority of peloids and in many beds appear to form the only type of peloids, the term pellet is often used instead of peloid. It should be stressed that, because the size of peloids is mostly less than or close to the thickness of the thin section, their amount is systematically overestimated (Jaanusson 1972). In some cases the values obtained for peloids represent fairly rough estimates. This is particularly the case when minute pellets are embedded in a micritic martrix in which individual pellet grains are difficult to distinguish from the surrounding micrite (particularly at 13.3, 14.3 and 15.9 m). The same problem arises when such pellets are very densely packed.

In some beds many skeletal grains have a distinct micritic envelope (Fig. 12 B), and the micritized portion of the grain forms a substantial part of the rock volume. For the latter reason micritic envelopes were distinguished as a separate constituent in point counts.

Classification of limestones is an intricate problem because a limestone is normally composed of a mixture of many constituents (skeletal grains, peloids, sparry calcite, micrite, terrigenous mud, etc.) and the proportions between the constituents vary within wide limits. Based on arbitrary sets of proportions a great number of different rock types can be distinguished. Classification can

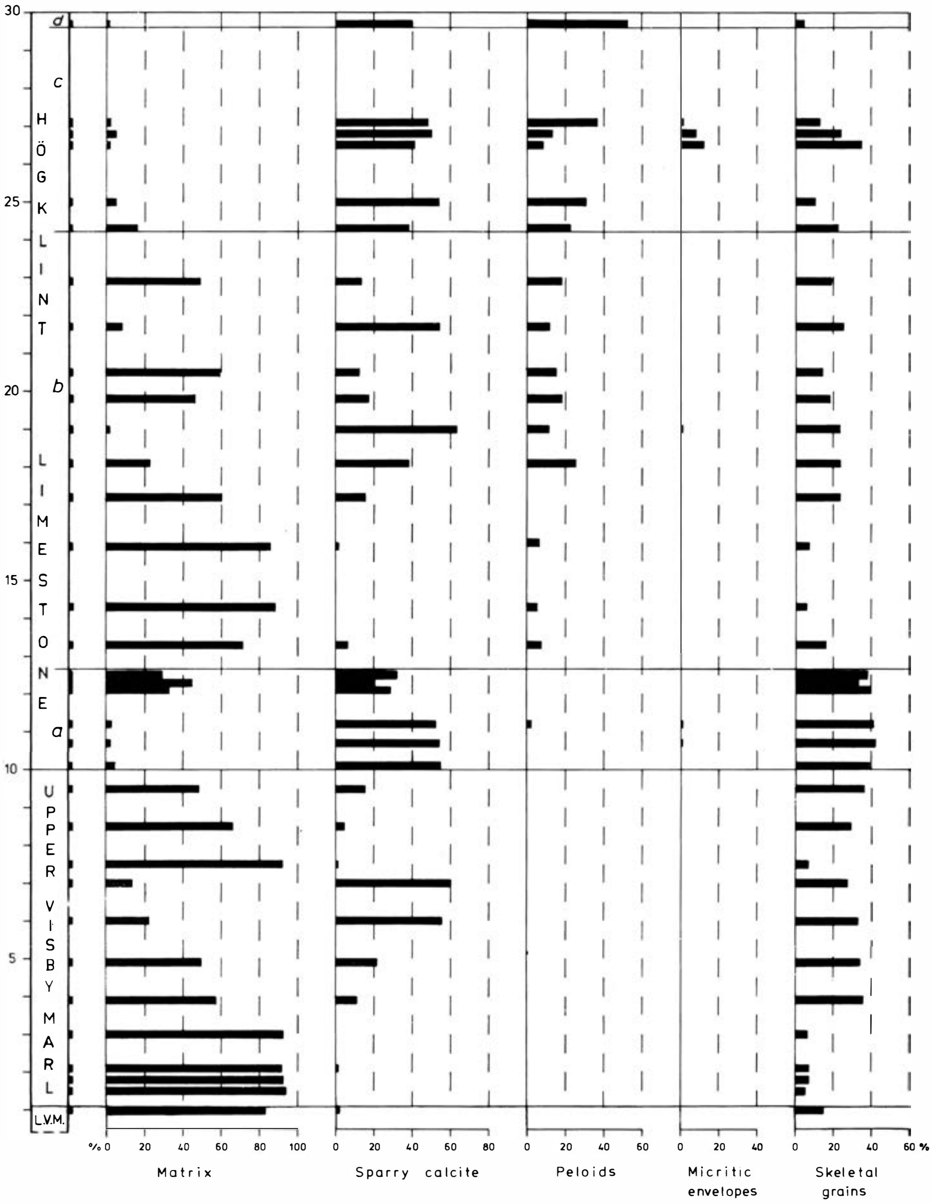

Fig. 5. Main microscopic constituents of the limestone based on point counting of thin sections.

also be based on other characteristics such as grain size or depositional texture. Irrespective of which classification is followed, reasonably representative data on the volumetric proportions of various constituents are of primary importance for characterizing a limestone and comparing it with other limestones. For the limestones of Vattenfallet such data are given in Fig. 5. For a study in which ecological background is involved, an emphasis on grain size is normally preferable.

Based on these premises the following simple classification is adopted here. Calcilutites contain less, and calcarenites more, than about 20 per cent of sand grains (Jaanusson 1952). If sand grains in a calcarenite are embedded in a micritic matrix, the rock is termed micritic calcarenite; if the content of presumably intergranular sparry calcite exceeds about 20 per cent, the limestone is called sparitic calcarenite. The content of peloids is recorded by adding "pelletiferous" or ("peloidiferous") to the term, except when they form more than 20 per cent of the rock and dominate by volume over sand grains. In the latter case the rock is termed pelletal (or peloidal) calcisiltite (provided that, as at Vattenfallet, the overwhelming majority of peloids falls into the size range of silt) which, like calcarenites, can be either micritic or sparitic. If the dominant grain size falls within the range of gravel, the rock is termed a calcirudite.

Compared with the original soft sediment, it should be noted that an originally early lithified limestone normally contains at least 50 per cent additional calcium carbonate precipitated as cement. This amount of calcium carbonate corresponds roughly to the pore volume in the soft sediment when lithification started. When determining the grain size of a soft sediment by weighing different grain size fractions, the pore volume is not considered, whereas when determining the grain size volumetrically, the pore volume, or the cement filling the original pores, forms a part of the volume of the sediment or rock. Thus, if the pore volume of the soft sediment was, say 50 per cent when lithification started, then the content of 50 per cent sand grains by weight would correspond to about 25 per cent sand grains by volume (Jaanusson 1972:226–227).

In the argillaceous beds of the Upper Visby Marl and Högklint *b*, aragonitic shells (gastropods, pelecypods, etc.) are mostly preserved as internal moulds, provided that they did not possess a thin, outer calcitic layer. This indicates that aragonite was mostly dissolved before the sediment became lithified, and that thus lithification started relatively late. In Högklint *c* many such fossils preserve the original shell volume, indicating that there lithification was earlier than the change in composition of the shell from aragonite to calcite. This suggests that prior to lithification the sediment of the argillaceous beds in the Upper Visby Marl and Högklint *b* became reduced in volume by compression to a greater degree than sediment now forming the limestone beds in Högklint *c*. In the friable marl the effect of compression is particularly noticeable through deformation of the shape of many large, thin-walled fossils. No special study of the diagenesis of the rock at Vattenfallet has been made, and it is also possible that some limestone beds in the Upper Visby Marl and Högklint *b* were lithified early. The effect of reduction of sediment volume on the grain size of the sediment or rock is shown by Martna (1955, Fig. 2). It should be noted that compaction also affects the content of terrigenous material. With decreasing pore volume less calcium carbonate can be precipitated in the voids and the relative proportion of terrigenous material in the rock increases. Thus, with respect to the content of terrigenous material the contrast between limestone beds and argillaceous beds is now greater than it was prior to lithification.

In parts of the Vattenfallet section the limestone is relatively inhomogeneous. This is particularly true in the Upper Visby Marl and Högklint *b*, Within a single thin section there occur patches of sparitic and micritic calcarenite, or calcarenitic and calcilutitic limestone. Much of the heterogeneity is demonstrably due to uneven bioturbation. In the upper part of the Upper Visby Marl as well as in parts of Högklint *b*, calcarenitic and calcilutitic beds frequently alternate. The surface of a thin section is too small to display correct proportion between different rock types within a bed, and the number of samples is too small to illustrate all vertical variations in lithology. Despite this, the series of thin sections that have been analysed microlithologically (Fig. 5) appear to provide a satisfactory basis for characterizing the rock. The lithological study is admittedly incomplete because only calcium carbonate constituents have been analyzed in some detail, whereas the terrigenous component has not been studied.

Lower Visby Marl (0.4–1.1 m)

No lithological change at the boundary between the Lower and Upper Visby Marl could be observed in the field. Only the uppermost bed of the Lower Visby Marl was studied microlithologically and no differences from the lowermost Upper Visby Marl could be noted.

Upper Visby Marl (1.1–10.02 m)

Up to about 3.6 m above sea-level the Upper Visby Marl consists of bluish-grey marl with nodules and irregular nodular beds, mostly one to three cm thick, of fine-grained argillaceous limestone. The limestone is a calcilutite, mostly with a low content of skeletal sand (Figs. 5, 6A) and normally with a high admixture of terrigenous clay. The sediment was a mixed carbonate and terrigenous mud.

In the main upper part of the Upper Visby Marl limestone predominates, forming irregular beds or nodules, mostly 2 to 4 cm thick, intercalated with soft

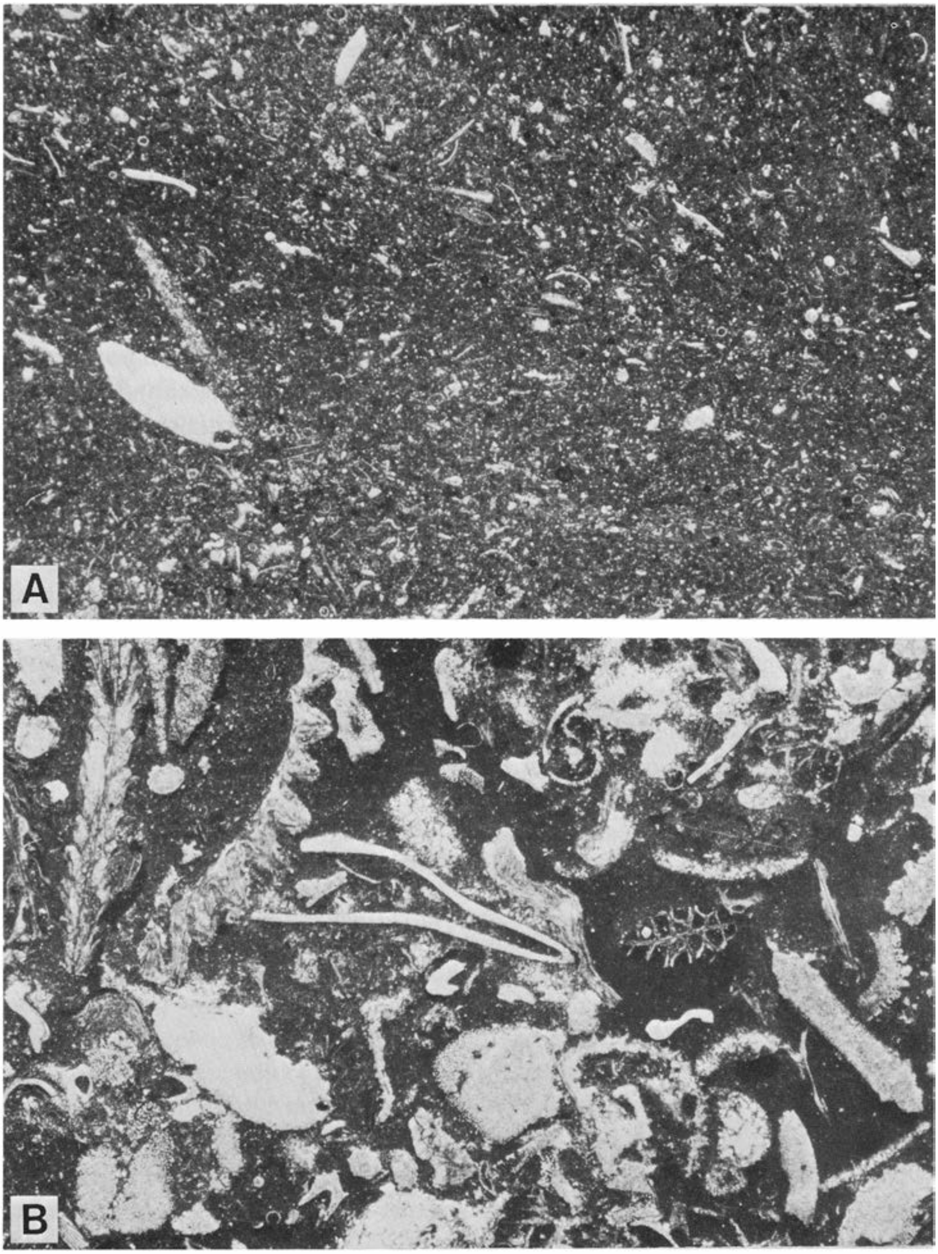

Fig. 6. A. Calcilutite, Upper Visby Marl at Vattenfallet, 3.0 m. The large skeletal grain to the left is an oblique cross-section of an *Atractosella* spicule. B. Micritic calcarenite, Upper Visby Marl at Vattenfallet, 9.6 m. Thin sections, ×15.

marl (Fig. 7). The grain size of the limestone varies (Fig. 5). Some beds (7.5 m) are as fine-grained as in the lowermost part of the section and originally formed the same kind of sediment. In some other beds (4.9, 8.5, 9.5 m) the rock is a micritic calcarenite (Fig. 6B). The sediment was a mud-supported skeletal sand. The limestone also includes beds (6.0, 7.0 m) with a high content of sparry calcite, most of which was originally precipitated as intergranular cement. In these beds the content of skeletal sand is also high (Fig. 5). The rock can be classified as sparitic calcarenite and the sediment was a largely grain-supported skeletal sand. In order to determine the proportion of the different types of limestone within this part of the section a far denser series of samples is needed.

In the micritic portions of the rock the micrite is fairly homogeneous in thin sections. In only a few cases could faint traces of flocculation be observed but it is uncertain whether these indicate pelletal structures. Much of the sequence shows traces of bioturbation.

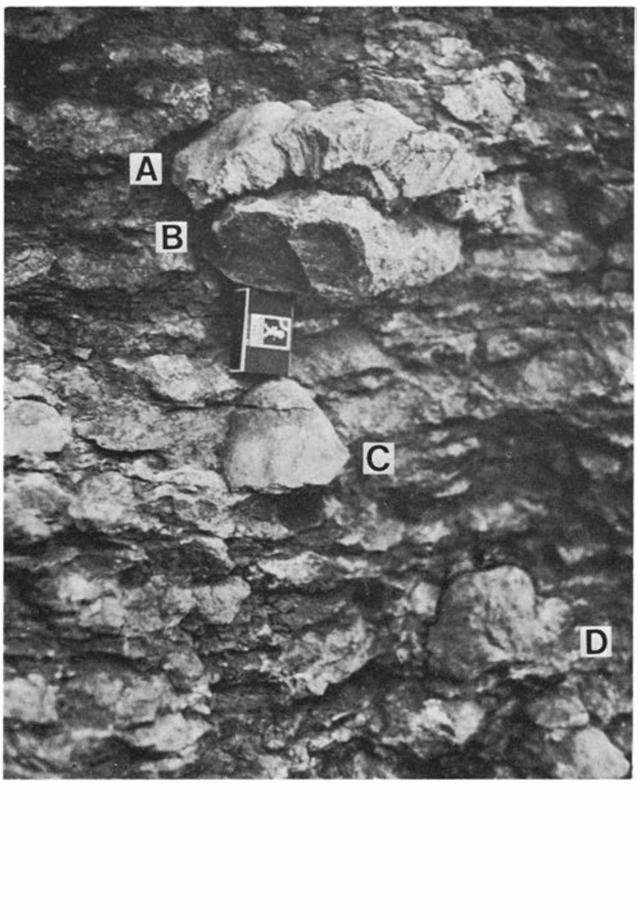

Fig. 7. Upper Visby Marl at Vattenfallet, 9.1–9.65 m. A. Colony of *Catenipora quadrata* encrusting *Densastroma pexisum* (B). Other colonies of the stromatoporoid *D. pexisum* are below the match-box (C) and in the lower right corner (D). All colonies are in original growth position and all stromatoporoids were resting on the sediment. Length of match-box 5 cm. Photograph Ulf Borgen, 1976.

The mound of unstratified limestone in the Upper Visby Marl

At the second waterfall a massive carbonate mound is developed in the upper part of the Upper Visby Marl (Fig. 8; Hedström 1910, Pl. 60:b). The visible height of the mound is about 3.5 m but the base is not exposed. Its top extends to the level of the lowermost beds of Högklint *a*. There the contact relationships between the stratified limestone and the mound are not quite clear but appear to indicate an abrupt change in lithology between the thick-bedded calcarenites and the mound rock. The change from the bedded Upper Visby Marl to the unstratified limestone of the mound is also fairly abrupt, but some marly intercalations can be followed into the mound almost horizontally, indicating that it did not protrude very much above the level sea-floor. The rock of the mound includes thin discontinuous argillaceous intercalations and pockets of soft argillaceous limestone.

The mound is one of numerous similar structures in the upper part of the Upper Visby Marl of northwestern Gotland (see Manten 1971:79–114), generally referred to as reefs. It is less well exposed than many others and does not form a satisfactory basis for a detailed study.

In order to examine the structure of the mound, a surface, measuring about one square metre and located about 2.2 to 3.3 m below its top, was cleaned with a steel brush, etched with hydrochloric acid, and stained with blue ink (Brood and Jaanusson,

Fig. 8. Etched surface of the unstratified Upper Visby mound at Vattenfallet, about 2.2–3.3 m below its top (about 7–8 m above sea-level). Light areas (A) at the base are favositid colonies (mostly *Angopora hisingeri*), in part displaced from the original growth position. Length of match-box 5 cm. Photograph Ulf Borgen, 1976.

assisted by Ulf Borgen, in June 1976). Although the best surface was chosen for etching, it is irregularly rough and with a varying slope that is mostly not perpendicular to the depositional surface (Fig. 8). After etching and staining the surface revealed the main compositional features of the mound but it was unsuitable for illustrating the structures. The tabulate and heliolitid corals were identified by Klaamann and the stromatoporoids by Nestor.

The massive limestone has no organic skeletal frame. It contains scattered colonies of tabulate corals and small stromatoporoids embedded in a mostly fine-grained, calcilutitic to calcarenitic limestone. The volume of colonial skeletons probably comprises 10 to 15 per cent of the total rock volume. Favositids dominate, mainly as *Angopora hisingeri*. Other tabulates and heliolitids include *Planalveolites fougti, Heliolites decipiens* and *Stelliporella* sp. Stromatoporoids, *Stromatopora impexa* and *Clathrodictyon delicatulum*, are represented by very small colonies. On the very top of the mound, at the level of the lowermost part of Högklint *a*, is a large colony (at least 0.5 m wide) of *Catenipora* n.sp. *a*. At the same level another halysitid colony was found, belonging to *Catenipora gotlandica* (Yabe) (RM Cn59638), encrusted by *Planalveolites* sp. Both halysitid species are rare but they are known elsewhere only from the Högklint Beds (Einar Klaamann, personal communication). The specimens from the mound were not entered in the logs because the levels in the mound do not correspond exactly to those of the adjacent bedded limestone.

The mound probably never projected above the seafloor more than 0.5 m, and it did not appear to have controlled deposition in its immediate vicinity. Nor could any influence from the mound be observed in the composition of the fauna of the adjacent bedded limestone.

A second, similar Upper Visby mound is probably located about 25 m ENE of that described above. The mound itself is not exposed at that point but the uppermost beds of Högklint *a* there form a distinct dome (Liljevall's *stuphäll*) the height of which was estimated by Liljevall to about a metre. The dome is reflected also in the lowermost beds of Högklint *b*.

Högklint a *(10.02–12.65 m)*

Högklint *a* consists of coarse-grained, mainly thick-bedded calcarenites with thin argillaceous intercalations. The change in lithology from the underlying Upper Visby Marl is fairly abrupt (Fig. 9). The microlithology of the limestone is uniform throughout the division, with a high content of both skeletal sand and sparry calcite (Fig. 5). Skeletal sand particles are frequently somewhat rounded. The sparry calcite was precipitated as intergranular cement although subsequently some neomorphic recrystallization has also taken place. The rock is a sparitic calcarenite (Fig. 10A) and the sediment was a well winnowed, grain-supported skeletal sand. Rare particles have been observed which might represent peloids (0.2 to 1.9 per cent of the rock volume). Coatings around skeletal grains also occur (0.2 to 1.7 per cent of the rock volume) but most of these represent algal structures.

Högklint b *(12.65–24.2 m)*

In its main lower part (12.65 to c. 20.2 m), Högklint *b* consists of thin (mostly 3

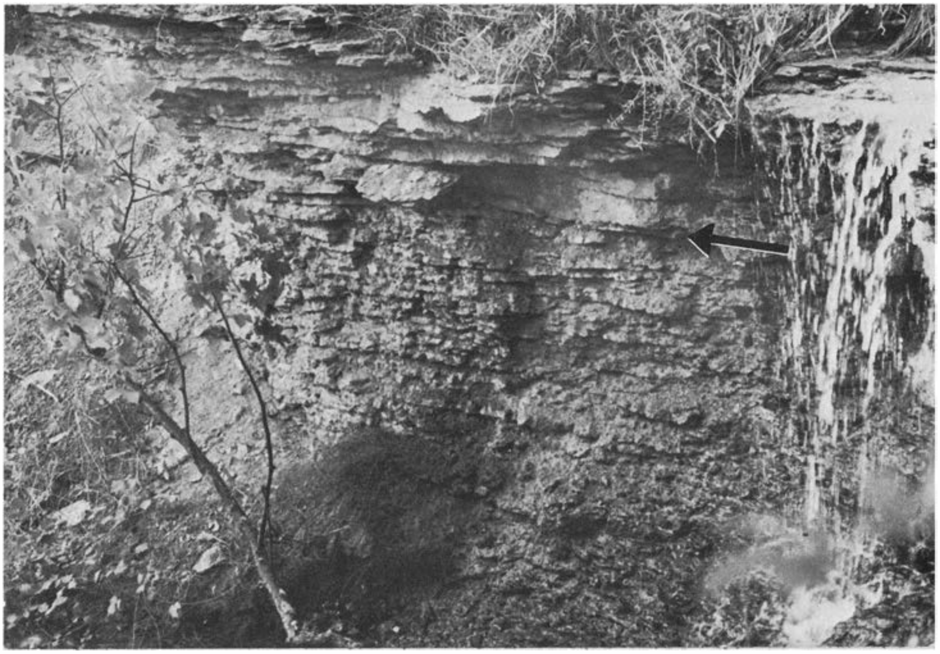

Fig. 9. The arrow points to the boundary between thin-bedded Upper Visby Marl and the overlying coarse-grained, thick-bedded limestones of Högklint *a*. Second waterfall at Vattenfallet. Photograph Stig Lindbom, 1977.

to 6 cm thick) predominantly irregular to nodular beds of grey fine-grained limestone intercalated with irregular argillaceous beds, up to 5 cm thick (Fig. 11). Many limestone beds show evidence of intensive bioturbation. In the upper part of Högklint *b* (c. 20.2 to 24.2 m) the bedding tends to be regular and some of the argillaceous beds are up to 10 cm thick. The top of the division is formed by a bed crowded with *Atrypa* sp. which Liljevall could follow over a distance of 10 m.

Thin section analysis shows that limestone in the lowermost 3.5 m of the division consists of a calcilutite with a low skeletal sand content (Figs. 5, 10B). Small pellets enter as an important constituent of the limestone. They are not always easy to distinguish from the micritic matrix and their relative proportion as given in the log (Fig. 5) is therefore approximate. In small sparitic patches within the calcilutite the pellets form distinct discrete particles suggesting that they were indurated grains. The predominant sediment was a pelletiferous carbonate mud intercalated with calcareous terrigenous mud. Adjacent to the dome above the probable second Upper Visby unstratified mound, a few sparitic beds (up to 11 cm thick) occur intercalated in the lowermost part of the calcilutitic portion of Högklint *b*. In these beds (studied from Liljevall's sam-

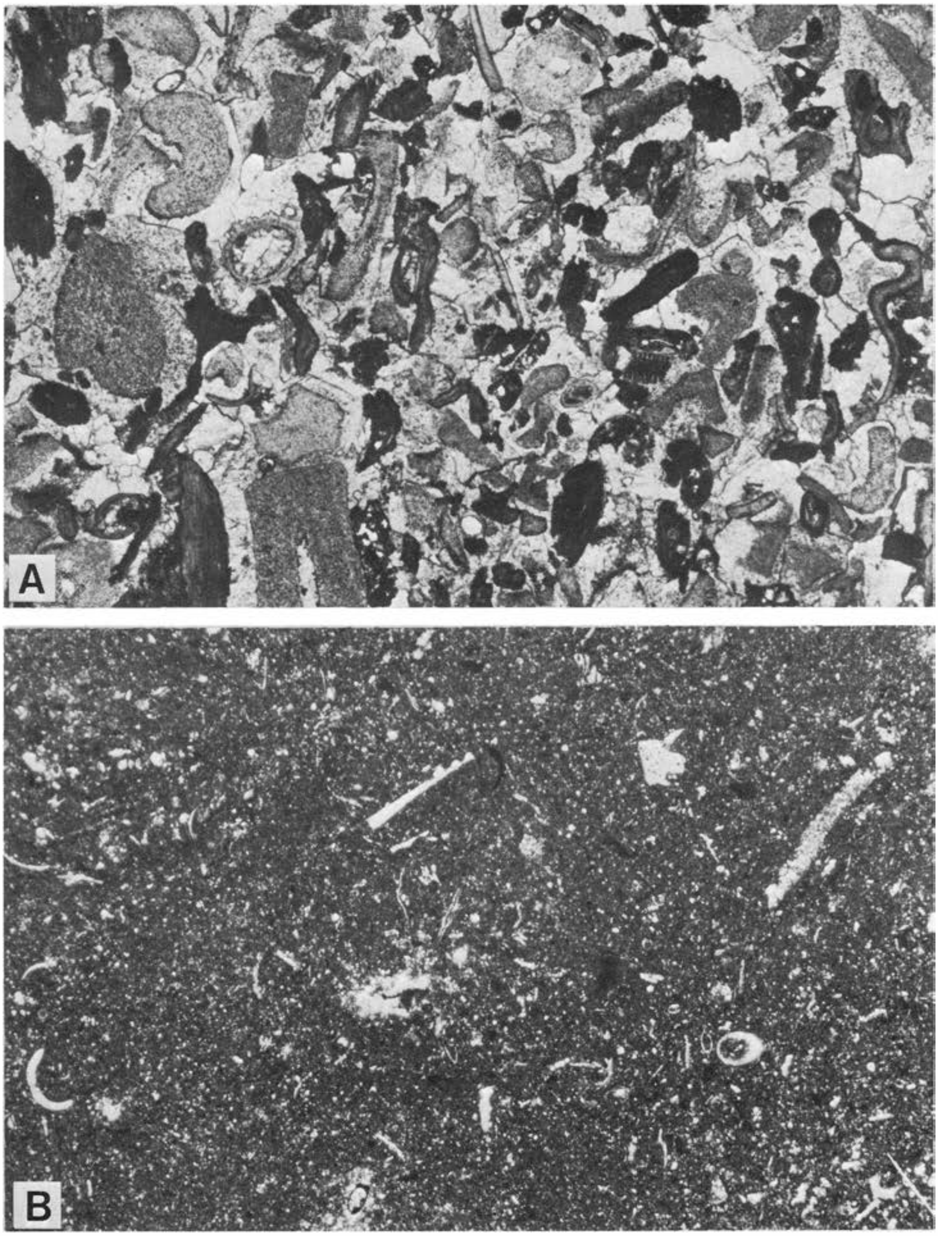

Fig. 10. A. Sparitic calcarenite, Högklint *a* at Vattenfallet, 10.7 m. The interspaces between skeletal grains are filled with sparry calcite. B. Calcilutite, lower Högklint *b* at Vattenfallet, 15.0 m. Thin sections, ×15.

Fig. 11. Stratification in the lower part of Högklint *b* at Vattenfallet, 14.5–15.0 m. Length of matchbox 5 cm. Photograph Krister Brood, 1976.

ples and not entered in the lithological log), pellets form an important constituent and the rock can be classified as sparitic pelletal calcisiltite to sparitic calcarenite. The intragranular cavities of skeletal particles are mostly filled with micrite, suggesting that some of the sediment may have been a residue formed by winnowing carbonate mud. In Liljevall's collections the calcarenitic beds are represented at 13.0–13.1 (at these levels large surfaces were available for collecting), 13.55 and 14.05 m.

In the main upper part of Högklint *b* (about 16.7 to 24.2 m) calcarenites predominate, in part micritic and in part sparitic. At several levels both types of rock have a patchy distribution within a single thin section due to uneven burrowing activities by organisms. The sand fraction is formed by skeletal particles whereas the silt fraction is dominated by pellets. Sparry calcite was originally precipitated mainly as intergranular cement. The carbonate sediment was a pelletiferous skeletal sand, in part mud-supported and in part grain-supported. Micritization phenomena are common, mainly in sparitic limestones, but micritic envelopes are quantitatively unimportant.

A bentonite bed at 17.0 m, 3 to 4 cm thick, forms an easily recognizable index horizon (Hedström 1910, Pl. 60:a). Additional bentonite layers occur at 18.05, 16.10, 15.33, 14.78 (a very thin layer), and 14.33 m (Laufeld & Jeppsson 1976). From about 15 m upwards fossils are partially silicified in places.

At the base of Högklint *b* (12.65–13.05 m) dwelling burrows or resting trails of varying size, belonging to the trace fossil *Conichnus* (Männil 1966), are not uncommon. Otherwise trace fossils are rare.

Högklint c *(24.2–29.6 m)*

Högklint *c* is formed of regularly bedded mainly light grey limestone with virtually no argillaceous intercalations. Many of the beds with a high pellet content show a lamination on polished surfaces and lack traces of bioturbation. Distinct cross-bedding was observed by Liljevall in the bed 26.45–26.55 m above sea-level. Indistinct ripple-marks occur at 27.65 m. From 26.2 m upwards, scattered, rounded, water-worn fossils of varying size occur in many beds. Much of the sequence above 28.8 m is calciruditic to conglomeratic.

Below about 28.8 m the limestone is alternatingly sparitic pelletal calcisiltite and sparitic pelletiferous calcarenite. The sand fraction is formed mostly of skeletal particles whereas the silt fraction is dominated by peloids (mostly pellets) (Fig. 12A). This rock has previously been referred to as oolitic but not a single ooid has been observed in thin sections or peels. As in other sparitic limestones of the section, most of the sparry calcite was originally precipitated as intergranular cement but neomorphic assimilation of skeletal grains has also taken place. Micritization phenomena (Fig. 12B) occur in all thin sections studied. Micritic envelopes are quantitatively unimportant except at some levels where they form up to 13 per cent of the rock volume (Fig. 5). At these levels part of the sand fraction is formed by peloids of various shape and size (Fig. 12B), many possibly representing completely micritized skeletal grains. Such grains also occur rarely at other levels. In this part of the section much of the sediment was originally a grain-supported pelletal silt to grain-supported skeletal sand.

In the uppermost part of Högklint *c,* above c. 28.8 m, the grain size increases and much of the rock is a sparitic calcirudite. Many gravel grains, 2 to 5 mm long, are rounded. They are in part skeletal (*Coenites,* echinoderms, *Solenopora,* stromatoporoids, corals, etc.) and in part pieces of pelletal limestone, lithified, eroded and rounded. Algal coatings around the grains are not uncommon. The interspaces between the gravel grains are filled either by sparry calcite or pelletal silt. Much of the original sediment was a grain-supported skeletal gravel.

Högklint d ("Pterygotus" *Beds; 29.6–30.0 m)*

This subdivision, although only 40 cm thick, has received wide attention

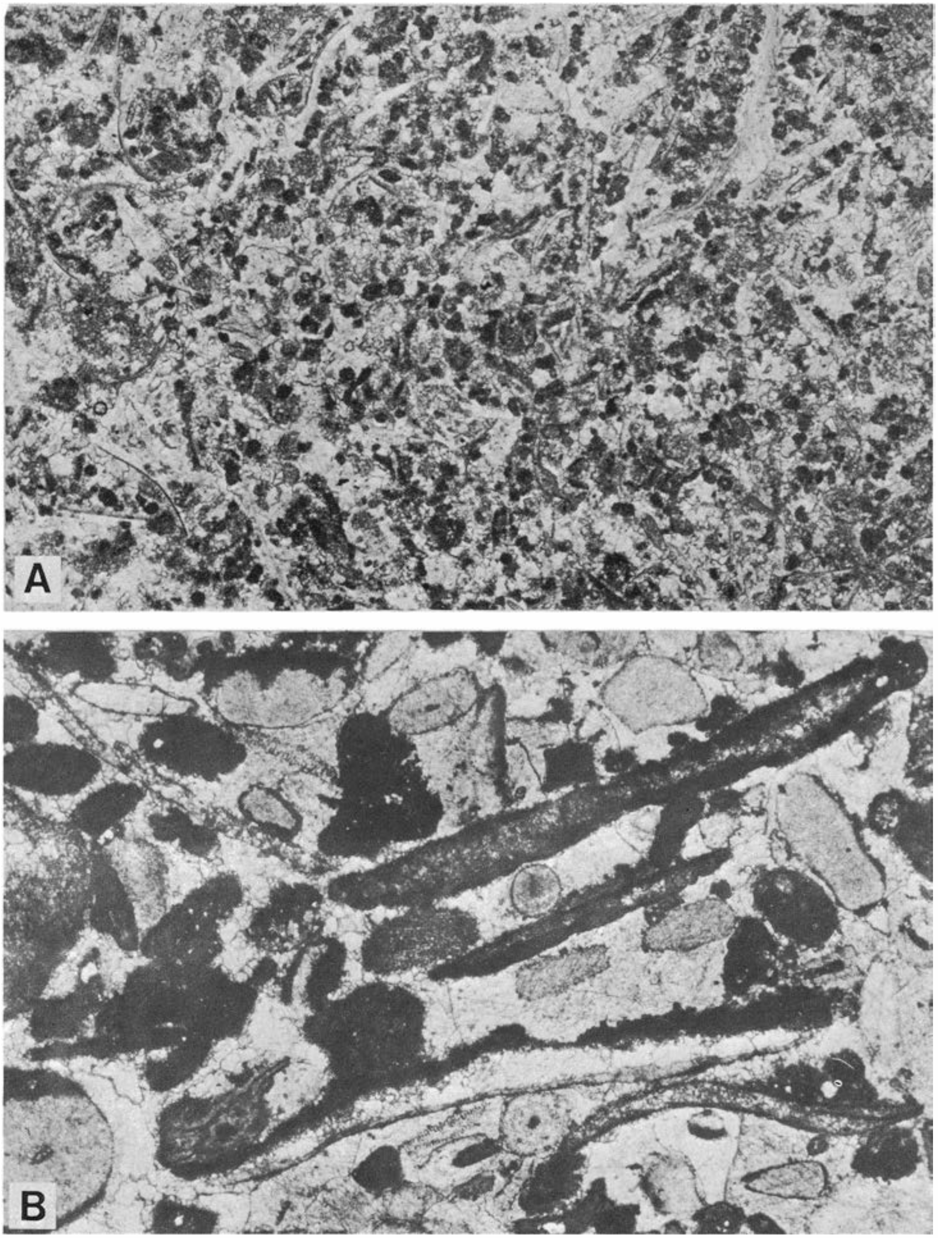

Fig. 12. A. Sparitic calcisiltite, Högklint *c* at Vattenfallet, 24.2–24.3 m. B. Sparitic calcarenite with numerous micritic envelopes, Högklint *c* at Vattenfallet, 26.45–26.55 m. Thin sections, ×15.

because of its remarkable fauna. It has commonly been called the "*Pterygotus* Beds", named after the eurypterid *Truncatiramus serricaudatus* (Kjellesvig-Waering, this volume) which was previously erroneously identified as *Pterygotus osiliensis* Schmidt (Lindström 1885; Thorell & Lindström 1885:4).

A detailed section of Högklint *d* measured in 1894, and situated at or close to Lindström's original scorpion-locality, was published by Hedström (1904; see also Hede 1940:29). A translation of Hedström's description is given below, in ascending order of the beds. The original numbers of the beds are retained, the text is somewhat abbreviated and terminology brought up to date.

8. 0.02 m. Dark grey "marlstone", wedging out laterally and replaced by grey, bituminous limestone containing beyrichiacean ostracodes.
7. 0.12–0.16 m. Grey bituminous limestone, intercalated by paper-thin layers of greyish "marlstone".
6. 0.08 m. Hard grey, dark grey to black "marlstone".
5. 0.06 m. Grey bituminous limestone with *Strophomena* (= probably *Valdaria*) and leperditiids (= *Herrmannina phaseolus catarractensis*).
4. 0.05–0.06 m. Soft, reddish, in places dark grey "marlstone", with very thin layers of limestone in the lower part.
3. 0.02–0.03 m. A thin, characteristic bed of reddish limestone or "marlstone", particularly rich in *Strophomena* sp. (= *Valdaria testudo*).
2. 0.02–0.03 m. Soft, reddish, in the lower part grey "marlstone" with very thin discontinuous layers of grey limestone. The bed is rich in scolecodonts, pieces of *Pterygotus* (= *Truncatiramus* and other eurypterids), *Eatonia* (= probably mainly *Septatrypa subaequalis*), etc. This is probably the bed in which *Palaeophonus nuncius* (Thorell and Lindström) was found. The boundary with the underlying bed of limestone (top of Högklint *c*) is uneven.

Högklint *d* thus includes several different lithologies, most of which are represented in the large collection of rock samples, labelled as "*Pterygotus*-lager" or "*Pterygotus*-märgel", excavated from the original scorpion-locality by Lindström, Liljevall, and others. The material includes three main lithologies: (1) a soft, greyish marl with abundant scolecodonts and remains of eurypterids; (2) a bed of grey limestone abounding in *Valdaria testudo;* and (3) grey limestone rich in and often crowded with *Herrmannina*. It is possible that these rock samples came from beds 2,3 and 5, rexpectively. On the other hand, there was obviously some rapid lateral variation in the lithology, and in places where some of the material was collected the sequence may not have conformed exactly to the section described by Hedström.

Bed 2 is formed of an argillaceous, fine-grained, fairly soft rock abounding in densely packed small carbonate pellets. The somewhat flattened condition of thin-walled skeletons embedded in the rock indicates that the sediment has undergone some compression, although the degree of volumetric decrease is difficult to estimate. This suggests that the lithification was late relative to the limestone beds, in which, as a rule, similar fossils retain their original convex-

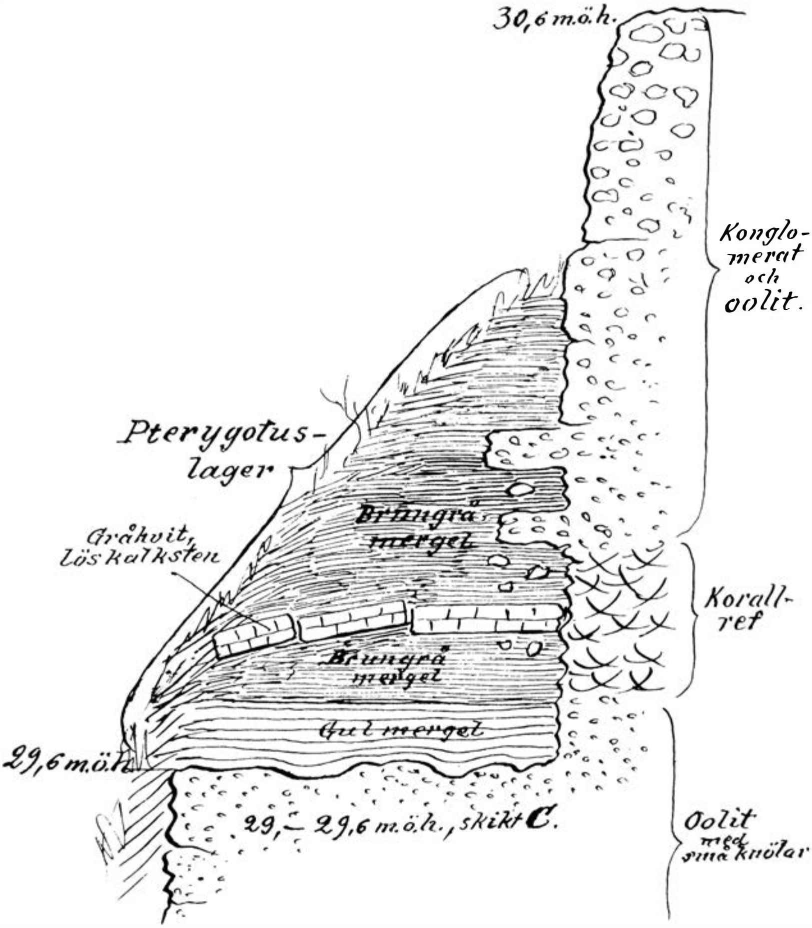

Fig. 13. Liljevall's original, "somewhat schematic" drawing of the depositional relationships between the *"Pterygotus"* Beds (Högklint *d*) and adjacent beds of mainly conglomeratic limestone. Vattenfallet, just north of the sixth bridge (see Fig. 2).

ity. In fact, the rock is still not well lithified and can be easily disaggregated. Thin sections show an indistinct fine lamination and a distinct preferential orientation of elongate skeletal grains (mostly ostracode valves) parallel to the lamination. No traces of bioturbation could be observed. The rock is difficult to classify but pelletal marl may be an appropriate term. The sediment was a kind of mud-supported pelletal silt.

For the composition of a limestone bed, see the log (Fig. 5). The rock is a sparitic pelletal calcisiltite. In places the pellets are densely packed, in other places intergranular sparry calcite is common. No lamination or preferential orientation of elongate skeletal grains can be observed. The sediment was a grain- to mud-supported pelletal silt.

The general concept of stratigraphical relationships of the "*Pterygotus*" Beds (Thorell & Lindström 1885; Hedström 1904, 1910; Hede 1940, and others) has been one in which the division conformably overlies bedded Högklint limestones and is overlain by beds now classified as the Tofta Limestone. According to Hedström (1910) the underlying beds (Högklint *c*) "become gradually coarser and at the same time nodulous and conglomerate-like towards the top". The "*Pterygotus*" Beds, in turn, are "covered by a conglomerate with water-worn gastropoda" which "reminds us in certain respects of the discordance-layer in Lindström's old quarry to the south of Gustavsvik", that is, the base of the Tofta Limestone. However, according to the description and drawings of the relevant portions of the Vattenfallet section in Liljevall's diary of 1908, the depositional relationships of the "*Pterygotus*" Beds differ essentially from those generally assumed.

Liljevall's section through the "*Pterygotus*" Beds was excavated on the slope of the eastern bank of the brook, just north of the so-called sixth bridge (Fig. 2) and about 30 m northeast of Lindström's scorpion-locality. There, remains of the "*Pterygotus*" Beds, somewhat disturbed by solifluction and transected by roots, were found resting discordantly against a natural vertical "wall" (Fig. 13) of limestone beds which were continuous downwards with, and similar to, the top of Högklint *c*. These limestone beds were overlain by a reef-like accumulation of dome-shaped corals and stromatoporoids (29.7–29.9 m), and a conglomerate with upwards-increasing pebble size (29.9–30.6 m). Some beds of the "wall" projected somewhat into the "*Pterygotus*" Beds (Fig. 13), and pebbles derived from the rock of the wall were found embedded in the "*Pterygotus*" Marl. Liljevall's conclusion was that the sediment forming the wall must be older than the "*Pterygotus*" Beds, and that it was not only lithified prior to the deposition of the "*Pterygotus*" Beds but also deeply eroded. "*Pterygotus*" Beds were then deposited in depressions on the eroded surface.

At Lindström's original scorpion-locality some remains of the "*Pterygotus*" Marl were still accessible to Liljevall on the bottom of a shallow pit which represented the last remains of the once extensive excavation. Here too, bedded limestone of the same general type as that forming the steep "wall" farther to the north was found by Liljevall to occur at the level of the "*Pterygotus*" Marl, but the contact relationships could not be observed in detail. This indicates, according to Liljevall, that at that locality the "*Pterygotus*" Marl was also deposited in a depression formed in "semi-lithified" and eroded beds of older limestone. It should also be noted that samples of the "*Pterygotus*" Marl from the scorpion-locality contain occasional pebbles of rounded stromatoporoids and corals.

Tofta Limestone?

No exposure available to Liljevall showed the contact between the "*Pterygotus*" Beds and the overlying beds. According to Hedström (1904) the "*Pterygotus*" Beds were overlain by a conglomeratic limestone which was almost brecciated in the lowermost part. He noted that the "pebbles" consisted of a finely crystalline limestone embedded in a yellowish matrix of fairly soft limestone. The stratigraphical attribution of these beds is not clear. Some samples obtained by Liljevall at Vattenfallet from beds above 30 m contain *Thecia podolica* (c. 31 m; identified by Klaamann), *Vikingia* cf. *nestori* (31.8 m; identified by Nestor), and the algae *Hedstroemia halimedoidea* and fenestral non-skeletal oncolites (31.5 m; identified by Riding).

Depositional environments

It is difficult to reconstruct depositional environment based on data from a single section, particularly within an area where topography of the nearby sea-floor was variable. Ideally, this report should have been complemented by a regional lithological study of the Upper Visby Marl and Högklint Beds at least in the immediate vicinity of Vattenfallet, but this was far beyond the scope of the project.

When interpreting depositional environments of ancient limestones, absolute depth can rarely be determined, and in general the relative depth can only be roughly reconstructed in terms of whether water during deposition at any one time was deeper or shallower than it was when underlying or overlying beds were deposited (Bathurst 1967). For interpretation of relative depth, data on the relative level of water energy may yield useful information. In a sea, water energy has some relationship to depth, in that there is an overall probability that with increasing depth water energy decreases rather than increases. However, this is true only in general terms, and even in very shallow water a wide amplitude of water energies, from very high to very low, can be represented. The factors that control water energy, such as slope of the sea-floor, exposure, current velocity, etc., are very difficult to reconstruct. Moreover, in shallow-water carbonate sediments the trapping and binding action of plants and the possible occurrence of gelatinous mats on the sediment surface may effect the grain-size distribution so that it does not reflect the real water energy level.

The presence of algae throughout the Vattenfallet section (Fig. 20) indicates that deposition took place entirely within the depth range of the photic zone. The lower, calcilutitic part of the Upper Visby Marl was deposited in a fairly constant low-energy environment, whereas during deposition of the upper part of the division the water energy fluctuated, at times reaching moderately high levels. Depth of the sea is difficult to estimate, but the presence of a probable dasycladacean alga almost down to the base of the section indicates that it was less than 100 m even in the lowermost Upper Visby Marl (Riding, this volume). That water depth decreased successively during deposition of the Upper Visby Marl has been repeatedly suggested (Hadding 1941, Manten 1962, etc.).

In the Upper Visby Marl exposed in the cliff along the beach north of Kneippbyn the orientation of 38 tabulate and heliolitid colonies was recorded in two calcarenitic and adjacent marly beds. About 75 per cent of the these colonies are in their original growth position, and 20 per cent are tilted relative to the horizontal (of which a part might be in original growth position). Two of the colonies were lying upside down, indicating that at times water energy was sufficiently high to move small coral colonies. In this context it should be remembered that the weight of a living or dead tabulate or stromatoporoid colony, prior to the voids in the skeleton becoming filled with sediment or cement, was but a fraction of its present weight. Displacement of coral colonies also indicates that skeletons of other groups may have been moved around or transported, particularly small and light shells. That this has happened is evident from the disorderly accumulations of skeletons of various macrofossils in some beds of sparitic calcarenites.

The origin of small, unstratified mounds in the upper part of the Upper Visby Marl is not yet understood. Mounds similar to that at Vattenfallet are not uncommon and a few of them, at Kneippbyn and Snäckgärdsbaden 1, were briefly examined during a post-graduate student field course in June 1967.

Some reasonably smooth surfaces, approximately normal to the depositional plane, were etched with hydrochloric acid, stained with potassium ferrous cyanide as well as blue ink, and point counted in the field. No coherent organic frame has been observed in any of the mounds. Favositids, in particular *Angopora hisingeri*, dominate among colonial organisms. Scattered favositid colonies were found to form 8 to 13 per cent of the total area of the surfaces studied, and other colonial corals (heliolitids, halysitids and rugose corals) one to three per cent. Stromatoporoids are relatively rare and mostly represented by small colonies. If the growth of the mounds was controlled by organisms, the skeletal colonial organisms must have been supplemented by soft-bodied forms that have perished without trace. On the other hand, although skeletal colonial organisms do not appear to have been the main cause of the growth of the mounds, the content of tabulate corals in the mounds is significantly higher than in the adjacent contemporaneous bedded sequence.

The "anatomy" of the Upper Visby mounds differs from that of the upper part of the Högklint reefs where the core in places abounds in colonial skeletal organisms, almost all stromatoporoids, and where a skeletal frame might have been developed. The top of some Upper Visby mounds is at the level of the lowermost Högklint *a*, but after that their growth appears to have ceased in the Visby area. No continuity between the Upper Visby mounds and the Högklint reefs has been observed in that area.

The pronouncedly sparitic calcarenites of Högklint *a* indicate a further increase in water energy. This division has a fairly uniform lithology throughout its extent in northwestern Gotland. At Vattenfallet it is relatively thin whereas elsewhere the thickness reaches up to 15 m (Hede 1940). The distribution of Högklint *a* along the outcrop area is discontinuous, which indicates that the sediment accumulated as a series of skeletal sand banks, of varying size and unknown shape. Hede (1933, 1940) has stressed that even within a short distance from the Högklint reefs the lithology of the division begins to change, in that the thickness of the individual beds decreases and the sequence becomes increasingly more argillaceous. At a greater distance from the reefs the equivalent beds are formed of a thin-bedded dense to fine-grained limestone with thin intercalations of marl. Hede (1933, 1940) also pointed out that Högklint *a* forms the base of the Högklint reefs, and surrounds the basal portion of the reefs in many cases. Only in a few instances are the Högklint reefs known to rest on the Upper Visby Marl without intervening coarse calcarenitic beds (Hede 1933; Manten 1971). In some other cases the Högklint reefs start to grow higher upp in the sequence, but then it is not always clear whether the exposed section of the reef is cut along the periphery of the reef complex or is located centrally. The close association of Högklint *a* banks with overlying reefs suggests shat the skeletal sand banks formed a suitable substratum upon which many of the reefs were founded.

Some authors (Jux 1959; Manten 1971) have emphasized the importance of supply of crinoidal remains for development of "crinoidal limestones", including those in Högklint *a*. According to them the accumulation of "crinoidal limestones" is mainly the result of luxurious growth of crinoids on flanks of the reefs. This may be true for same reef flank deposits in the strict sense, but at Vattenfallet the accumulation of skeletal sand in Högklint *a* cannot possibly have been merely supply-dependent. Quantitative data (Fig. 77) show that in Högklint *a* about half of the skeletal sand grains belong to echinoderms, which is only some ten to fifteen per cent more than in beds below and above. The relatively high content of echinoderm sand grains in these beds is more probably associated with the general tendency of increased relative frequency of echinoderm grains when the grain size increases (Jaanusson 1972, Fig. 11). This, in turn, is dependent on the natural grain-size distribution of disintegrated echinoderm particles and the hydrodynamic properties of these particles. In Högklint *a* the sand fraction also includes, on average, more articulate brachiopods than in other parts of the section (Fig. 77), and many of these show rounded contours (in echinoderm grains the degree of secondary rounding is difficult to estimate because of their commonly original rounded shape). This, the winnowed character of the grain-supported sediment, and other characteristics show that Högklint *a* was deposited in an environment with a conspicuously higher level of water energy than in beds above and below. The most distinctive features in the lithology of Högklint *a* were a product of this high energy level.

The lithological change from the Upper Visby Marl to Högklint *a* is pronounced (Figs. 5,9), indicating that relative to the rate of deposition the change in water energy level was fairly sudden. A possible explanation for the relatively sudden change is that the sea-floor came within wave-base through a further decrease in water depth. However, other explanations are also possible and without knowledge of the geometry of the banks no safe conclusions can be made.

The calcilutites of the lower part of Högklint *b* at Vattenfallet indicate a considerable drop in water energy level, resulting in the deposition of carbonate and terrigenous mud. During that time low reef-like mounds and possibly also some low Högklint *a* banks were forming in the vicinity. The decrease in water energy might have been associated with a sheltered position of the Vattenfallet area behind moundlike elevations on the sea-floor. On the other hand, the change from sparitic calcarenites of Högklint *a* to argillaceous calcilutites of Högklint *b* seems to be a wide-spread phenomenon in the outcrop area of northwestern Gotland. This suggests that the decrease of energy may have been caused by factors which controlled deposition at least on a regional scale, such as increase in water depth. Without a detailed regional survey of the lithology of the equivalent sequence throughout northwestern Gotland, meaningful conclusions are difficult.

Higher up in Högklint *b* the water energy fluctuated, reaching moderately high levels during deposition of beds which now are sparitic calcarenites. The abundance of pellets indicates deposition in an environment in which water could be warmed up and calcium carbonate (possibly aragonite) precipitated to transform soft pellets into indurated grains. The size range of the pellets (0.4 to 0.7 mm) is close to that on the Great Bahama Bank (0.3 to 0.5 mm; Purdy 1963:342). The general depositional environment was probably in relatively sheltered, warm shallow water.

During deposition of the main lower part of Högklint *c* the same general environment prevailed, except that fluctuations in water energy level appear to have been smaller than during deposition of the upper Högklint *b*, reflected among other things by the almost complete lack of deposition of terrigenous mud. Beds with current bedding and the occurrence of water-worn skeletal pebbles indicate higher maximum levels of water energy than in Högklint *b*. Beds in which the skeletal grains are intensely micritized (Fig. 12B), have almost exact counterparts in the sediment of the Great Bahama Bank, for example in Bimini lagoon (Bathurst 1966). The relative increase of the average water energy was probably associated with decrease in water depth.

In uppermost Högklint *c* the sparitic calcirudites, with water-worn pebbles and gravel, in places apparently well sorted, suggest deposition close to or at a beach, and in any case within reach of wave abrasion. Thus during the deposition of the middle and upper part of the Högklint Beds the water became successively more shallow.

Liljevall's observation show convincingly that prior to the deposition of the "*Pterygotus*" Beds (Högklint *d*) the sediments of Högklint *c* were lithified to a certain degree and fairly deeply eroded. This suggests emersion and subaerial exposure, although submarine lithification and channeling may produce somewhat similar effects. In the depressions of the eroded surface the distinctive "*Pterygotus*" Marl was deposited, a laminated, fine-grained, pelletal calcareous mud. The lack of bioturbation is probably the main reason why delicate exoskeletons of the scorpion and eurypterids were preserved. The intercalated beds of limestone were probably bioturbated to some extent and may have been deposited in somewhat more agitated water than the marl. The general depositional environment of Högklint *d* was in very shallow, warm, and tranquil water in a sheltered position.

For references see the list of references at the end of this volume.