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Diagenesis of Lower Ordovician hardgrounds in Sweden

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With 5 Text-figures and 3 Plates

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1 m of Arenigian orthoceratite limestone has at least 10 – 20 hardgrounds. Glauconite crusts postdate some calcite cement. Calcite crystals are intergrown with glauconite, pyrite, and goethite. Inclusion in calcite protected some goethite from dehydration to hematite. No evidence of aragonite or Mg-calcite was found. »Ant-egg spar« (AES), a variety of microspar, consists of redeposited calcite crystals of early cement origin. Hardgrounds may represent much longer time than the sediment; they show evidence of highly impoverished biota. The carbonate mud is essentially allochthonous.
1 m arenigischer Orthocerenkalk hat wenigstens 10 – 20 Diskontinuitätsflächen. Glaukonitkrusten sind zumindest partiell jünger als Kalzitzement. Kalzitkristalle sind durchwachsen mit Glaukonit, Pyrit und Goethit. Durch den Einschluß in Kalzit wurde ein Teil des Goethits vor der Hämatitisierung geschützt. Hinweise auf Aragonit und Mg-Kalzit wurden nicht gefunden. »Ameiseneier-Sparit« (AES) besteht aus kleinen, umgelagerten Kalzitkristallen frühdiagenetischen Ursprungs. Diskontinuitätsflächen dürften weit längere Zeiträume als das Sediment vertreten; ihre Fauna war äußerst dürftig. Das Karbonatsediment ist im wesentlichen allochthon.

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Introduction

Next to the gneiss outcrop round the corner, the Lower to lower Middle Ordovician orthoceratite limestone might be the most familiar rock to inhabitants of Sweden. You will find splendidly structured, polished rectangles of this red or grey limestone in floors and staircases of official buildings and apartment houses, counters of post offices, hospitals, and banks, and if they lead you up the garden path in Sweden, you are likely to find yourself walking on raw flags of orthoceratite limestone.

This facies is described in papers by, amongst others, HADDING (1958), BOHLIN (1949), BOHLIN & JAANUSSON (1955), and THORSLUND (1960). It may originally have covered several hundred thousand km^2 in northern Europe. After prolonged erosion, remnants of it are left in scattered areas (Fig. 1). Its main characteristics are everywhere the same: It is a stratigraphically condensed, slightly argillaceous, calcilutitic to calcarenitic limestone the bioclastic components of which are mainly disarticulated and comminuted trilobite and echinoderm skeletons, without definitely autochthonous, benthic fossils, and with massive beds separated by subparallel, uneven, in many cases marly partings at inervals of mostly 2 to 20 cm. The comminution of the bioclastic components may be largely due to organisms (boring sponges, LINDSTRÖM 1979a; in certain beds also boring thallophytes, HESSLAND 1948). Many partings originated as hardgrounds (ORVIKU 1960; JAANUSSON 1961; LINDSTRÖM 1963).

The hardgrounds are results of interrupted sedimentation and cementation of superficial sediment. These processes were in part or entirely submarine (LINDSTRÖM, 1963). The nature and causes of cementation are essentially unknown. Mineralization, combined with activities of burrowing organisms, has given rise to a play of colours that renders many hardgrounds spectacular. Relatively little is known about this mineralization. It is the aim of the present papers to somewhat reduce this ignorance in a number of cases.

Hardground with radial calcite (lower Arenigian, Horns Udde).

The sea-cliffs of Horns Udde, Öland, display excellent sections through the lower part of the orthoceratite limestone. The succession encountered in these sections has been described principally by HADDING (1932), TJERNVIK (1956), and LINDSTRÖM (1963). As everywhere, the basal part of the orthoceratite limestone is relatively rich in glauconite grains. Bedding is irregular and laterally discontinuous, and limestone alternates with argillaceous greensand. Certain years this part, about 0.5 m thick and comprising some 10 beds in vertical succession, is essentially covered by beach pebbles accumulating at the base of the cliff. The age of this part (by conodonts) is uppermost Tremadocian to lower Arenigian. The bed concerning us here is situated 0.6–0.7 m above the base of the Ordovician. It contains a conodont fauna comprising *Oepikodus evae, Stolodus stola,*

Fig. 1: Location map, showing in generalized fashion areas with preserved Ordovician limestone of the investigated facies (diagonal pattern) and presumed areas of carbonate production (see Fig. 5; stippled). 1: Horns Udde; 2: Degerhamn; 3: Borghamn; 4: Hällekis; 5: Bjällum; 6: Yxhult; 7: Sjurberg.

and *Paroistodus parallelus,* as well as worn specimens of *Prioniodus elegans,* which fauna dates it as belonging to a narrow interval low in the lower Arenigian Billingen Substage. It is 5 cm thick and consists of three layers. The top and base consist of grey calcilutitic limestone rich in glauconite and with irregular mottles of pale grey limestone without glauconite. There are reddish phosphorite fragments a few mm in size. The middle layer is a pale grey calcilutite the upper surface of which is developed as a smooth, non-mineralized discontinuity surface. On the irregular lower surface there are roughly hemispherical aggregates of radially arranged, yellowish calcite crystals (Pl. 1, Fig. 1–2). The radius of these aggregates is about 15 mm, and their spacing averages about 5 cm, although some aggregates are in contact with one another. The bed is referred to by VAN WAMEL (1974; Fig. 8).

The middle bed is disrupted in several places. Where this is the case the mottled glauconitic limestone appears to be continuous from the base to the top of the bed. The glauconitic limestone contains lumps and irregular flakes of light grey limestone nearly free of glauconite. These observations indicate that the light grey limestone consolidated before the glauconitic layers surrounding it, and that some perturbation occurred before the latter became consolidated as well. Parts of the light grey limestone were not yet completely rigid when the movements took place: they contain thin anastomosing cracks and small vugs filled with clear calcite. The upper layer of glauconitic limestone could have been deposited on the discontinuity surface after the latter had formed in direct contact with sea water; movements within the sediment could later on have established continuity between it and the lower glauconitic layer. In view of the apparent identity in lithology between the upper layer and the lower one, it appears, however, at least equally probable that they originated as one layer supporting the light grey layer. As the latter became partially cemented and developed radial aggregates on its lower surface, it was disrupted and foundered into the weak substratum. If this was the case the upper glauconitic layer formed by extrusion from below. The light grey limestone is a carbonate mudstone with less than 10% identifiable bioclastic components, mainly trilobite fragments. The mudstone consists of microspar with a crystallite size of ca. 5–10 μm. The trilobite fragments are structurally well preserved.

The most interesting diagenetic feature is the radial calcite aggregates occurring on the lower face of the hardground. The calcite crystals typically radiate from a single point; crystal cross sections are proportional to the distance from this nucleus. The shape of crystal cross sections is irregular, with serrated margins. The serration of the margins corresponds to flutes occurring in strictly radial arrangement on the contact surfaces between crystals. Most crystals are optically perfect, without undulose extinction or division into sub-crystals. The c-axis is radial. As far as could be ascertained, this condition extends to the nucleus of the aggregates. The peripheral terminations are convex; many are rounded rather than coincident with cleavage. The crystals are rendered orange yellow by finely dispersed goethite and minor amounts of hematite. The goethite is concentrated in particular near the periphery of the aggregates, as well as along crystal boundaries within the aggregates. Growth vectors within the crystals are outlined by densely spaced trails of particles consisting i. a. of goethite. Zones of clear calcite occur at various intervals along the crystal axes. In several crystals the last growth zone to form consists of clear calcite enveloping a goethite rich zone. Intergrowth of calcite with glauconite and pyrite occurred at various stages, including the last one. The intergrowths can be either irregularly anastomosing or fibrous in the direction of growth vectors (Pl. 3, Fig. 5–7).

Microprobe examination of four areas of polished section through the radial calcite failed to yield evidence of the presence of magnesium, strontium, or manganese. Iron occurs as goethite, hematite, and pyrite. However, its presence in the carbonate lattice could not be demonstrated. It is evident that much of the carbonate growth took place during stages with oxidizing intra-sediment conditions, when goethite was formed and little FeII was available for inclusion in the carbonate lattice. On the other hand it is possible that FeII available during anoxic stages was bound by sulphide ions that were present in abundance. Hence this iron was not available for the carbonate, either.

The striations described as growth vectors tend to fan out, in many cases with perceptible curvature, from the central axis of the crystal. A shown by Fig. 2, this implies surface increment distributed over the whole growth front, something to be expected in a relatively permeable matrix. Because of their orientation at different angles to the optical axis of non-undulose monocrystalline calcite, the growth vectors are not likely to be vestiges of densely spaced, acicular crystals of either calcite or aragonite. The growing elements of the aggregates were the whole calcite crystals, as evidenced by those cases of growth zonation and crystal terminations that do show crystal faces. For these reasons, the arguments graphically illustrated by Fig. 2 should not be regarded as an attempt to contribute to the discussion on radiaxial calcite and other similar phenomena involving undulose extinction and sub-crystal mosaics (BATHURST 1958, 1971, KENDALL & TUCKER, 1973, KENDALL 1977, KENDALL & BROUGHTON, 1978). The goethite most likely formed through oxidation of pyrite; otherwise, it is difficult to explain its spatially restricted concentrations. In its immediate neighbourhood there are intact aggregates of pyrite. That the formation of goethite took place during phases of early diagenesis is indicated by the following circumstances:

1. Goethite occupies zones in the interior of calcite crystals.
2. Zones with goethite in the interior of calcite crystals can be sealed off by a youngest zone of clear calcite; hence, the goethite did not form by oxidation of pyrite after the calcite had crystallized.
3. Pyrite occurs within calcite crystals in zones younger, as well as older, than zones containing goethite. Thus, anoxic conditions leading to sulphide enrichment alternated in time and probably also in space with oxidation of sulphide and formation of goethite.

The radial calcite aggregates probably formed before the matrix of the glauconite rich limestone was cemented. They deplace considerable volumes of the latter. If this were the effect of crystallization within a rigid frame of glauconitic limestone, one would expect either grains of glauconite scattered within the radial aggregates, or a zone greatly enriched in glauconite grains enveloping the latter. Contrary to this, there are but very few glauconite grains, trapped along certain crystal boundaries within the aggregates, and the distribution of glauconite surrounding the aggregates is apparently as random as anywhere else within the sample. Furthermore, the mode of calcite growth suggested by Fig. 2C probably requires relatively great permeability of the surrounding sediment. Cement would be a hindrance.

The following observations indicate that the radial aggregates (and the cement of the hardground from which they project downwards) formed during early diagenesis, i. e., in contact with sea-water.

1. Intergrowth of calcite crystals with glauconite (Pl. 3, Fig. 5).
2. Intergrowth of calcite crystals with pyrite.
3. Pyrite occurs as a thin sheath on crystal boundaries, even in peripheral parts of the radial aggregates. The sulphide is likely to have formed in contact with seawater (BERNER 1970; HALLBERG 1968; GOLDHABER & al. 1977).

Glauconite coated hardgrounds (lowermost Arenigian, Yxhult).

In Swedish outcrops of lower Arenigian limestone, hardgrounds with a skin of glauconite or a thin zone of glauconite impregnation are a common feature. In the quarries at Yxhult, by Hällabrottet, 18 km S of Örebro (see for instance TJERNVIK 1952 and 1956) the lower Arenigian comprises a 4 m thick succession of grey limestones with glauconitic discontinuity surfaces at several levels.

The Latorpian/Volkhovian boundary (see, for instance, MÄNNIL 1966) is situated at a slightly variable distance of about 4 m above the Cambro-Ordovician boundary. The lowermost 30 cm of the Ordovician consists of beds rich in granular glauconite. The figured sample to be discussed in the following (Pl. 1, Fig. 3) is from the upper part of this basal succession. It was collected by A. R. Hadding, Lund, who gave it the number 6015. It contains a conodont fauna comprising *Paroistodus proteus, Acodus deltatus,* and *Paracordylodus gracilis,* which dates it as lower Latorpian (Hunneberg Substage).

The sample is a good representative of the Latorpian succession of Yxhult. The dominant rock is a carbonate mudstone with less than 10% bioclastic components dominated by trilobite fragments, but with small orthoid brachiopods as important subordinate participants. There are two distinct microlithologies: microspar with crystal diameter of about 5 μm and »ant-egg spar« (AES, see below) with oblong crystals, »ant-eggs« about 10 μm thick and 20–30 μm long.

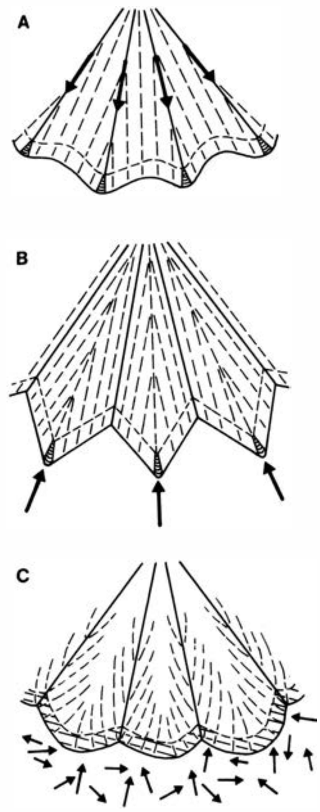

Fig. 2: Three postulated modes of radial growth of calcite crystals (among –perhaps – several possible). Arrows indicate dominant transport direction of solution from which calcite crystallizes. Broken radial lines indicate growth trajectories within single, optically homogeneous crystals (*not* = subcrystal boundaries). Linear shading indicates where surface increase occurs. An outermost growth stage is delimited by a broken line. A: Centrifugal solution transport, with surface increments at crystal boundaries; growth trajectories diverge from the boundaries. B: Solution transported at slow diffusion rates from outside; surface increments at crystal apices. Growth trajectories diverge from apices and may be parallel to boundaries of crystals. C: Solution brought from adjacent sediment, the permeability of which is good in all directions; surface increments distributed over entire surface. Growth trajectories curve away from central axis.

The sample consists of three layers. The lowermost contains numerous glauconite grains as well as glauconite encrusted irregularly shaped clasts of grey carbonate mudstone. The clasts vary in size from a few millimetres to several centimetres. The upper boundary of this layer is a glauconite inpregnated discontinuity surface. The middle layer is graded, with abundant glauconite grains and a few glauconite coated limestone clasts in the lower part and sparse glauconite grains in the upper part. The limestone clasts are like those of the lower layer. The middle layer has a relatively smooth upper boundary with a 4–5 mm thick glauconitized zone that gets hazy downwards. The uppermost layer is essentially free of glauconite.

From the upper hardground there extends a 4.5 cm deep and as much as 3.5 cm wide pit. The transition between the upper hardground and the walls of the pit is smoothly rounded. The pit cuts through the lower hardground and the underlying limestone. The glauconitized zone of the upper hardground continues down the walls of the pit to a depth of about 15 mm.

Below this, there follows a zone without glauconite crust. Below 20 mm the bottom of the pit again is glauconitized. The pit is surrounded by a zone enriched in pyrite. This zone is situated about 2 mm from the walls of the pit and is itself 1–5 mm thick. In places it is subdivided into two parallel zones, suggesting discrete waves of sulphide precipitation. Pyrite crystals are mostly in the size range 10–20 μm. However, large aggregates occur at certain boundaries of fossils that evidently served as channels of percolation. The pyrite zones do not fully extend to the upper glauconitized zone. This suggests that glauconitization of the upper hardground and pyritization occurred in somewhat different environments. Pyrite occurs as intergrowths with calcite in the lower parts of certain glauconite and calcite filled cracks that extend down the pit boundaries.

There is evidence of two stages of filling of the pit. The first of these stages is represented by a light yellowish grey carbonate mudstone with minor amounts of fossils and glauconite. At the second stage there formed a pocket crammed with convex-downward trilobite fragments. This pocket is surrounded by the carbonate mudstone of the first stage. The main part of the uppermost limestone layer of the sample is a still younger deposit.

Since phases of pyritization and glauconite encrustation are represented by clasts predating the lowermost glauconitized surface, the sample records a relatively long and complex history of sedimentation and early diagenesis. There is no evidence of oxidation of the entire sediment during the time represented.

The microscopic picture is that glauconite occurs as matrix, i. e., it encloses sediment particles and joins them into a firm structure. Glauconite matrix is restricted to hardgrounds, crusts surrounding several carbonate clasts, and abundant, small fragments of glauconite crust. The principal kinds of enclosed particles are »ant-eggs« and fragments of fossils, mainly trilobites.

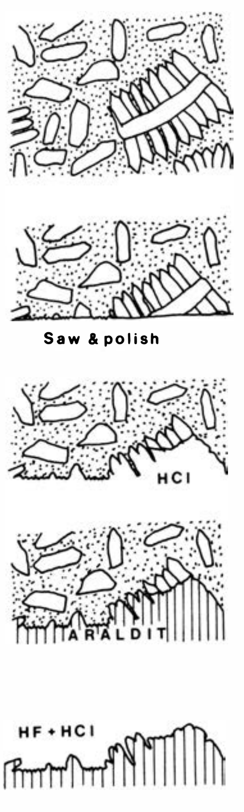

Fig. 3: Preparation of araldite mould of calcite particles enclosed in glauconite (Pl. 2, Fig. 1,2). Glauconite is stippled. From a polished section through the specimen calcite is removed by etching (HCl); araldite is added and allowed to harden. After treatment with HF the resulting fluorides are removed by HCl.

The »ant-eggs« are single crystals of non-magnesian calcite, about 5–15 μm thick and 10–40 μm long. In thin section, particularly where cemented by calcite, they appear rounded. Scanning electron optic studies suggest the presence of crystal faces on many »ant-eggs«. The crystal shape can best be described as prism-like, since it appears an uncertain undertaking to assign it specifically to any of the numerous surface combinations occurring in calcite (Pl. 2, Figs. 1, 2). The technique of preparing the sample for the electron optic pictures is illustrated by Fig. 3.

Fossil fragments commonly have a sheath of columnar calcite crystals. In thin section these sheaths appear palisadelike (Pl. 2, Fig. 3) if cut at right angles to the host shell and equant-granular if cut tangentially to the latter. The electron optic aspect is one of discrete, subparallel, prism-like crystals (Pl. 2, Figs. 1, 2). The dimensions of the overgrowth crystals are like those of the »ant-eggs«. It is suggested that most »ant-eggs« formed as overgrowth crystals that were liberated through disintegration of the host shell. Trilobite shells in different states of disintegration are common in the investigated beds; it is evident that they were less resistant to destruction than the overgrowths. For instance, trilobite fragments partly or entirely replaced by glauconite are rather common at the hardgrounds. In these cases, the columnar calcite coatings, if present, appear intact.

Replacement of calcite cement by glauconite has not be observed. Glauconite cementation apparently took place before ultimate cementation by calcite. Because pyritization, like glauconization, must have required some permeability of the sediment, this process, too, must have occurred before the pores were filled by calcite cement. Hence, the hardgrounds formed on imperfectly cemented rock. It is probable that the surfaces at which glauconitization and pyritization originated were in immediate contact with sea water. This includes the walls of the 4.5 cm deep pit.

Pinnacled hardground in red orthoceratite limestone (lowermost Volkhovian, Kinnekulle).

In the large limestone quarry of Hällekis, Kinnekulle, there is an unbroken limestone succession from the lower Volkhovian (mid-Arenigian) to the Uhakuan (Llandeilian). The lowermost part of this succession is red. The basal bed of red limestone rests on light greenish-grey, marly Lower *Didymograptus* Shale (TJERNVIK 1956, p. 142). It is 8 cm thick and contains a succession of at least 7 yellow-stained discontinuity surfaces (Pl. 1, Fig. 11). *Drepanoistodus forceps, Periodon flabellum, Microzarkodina flabellum, Scolopodus rex,* and rare *Baltoniodus triangularis* were collected from this bed. These conodonts date the bed as basal Volkhovian.

The lowermost hardground has the strongest yellow stain. It consists of steep-sided pinnacles mostly 1–3 cm wide horizontally, and reaching a level about 4 cm from the base of the bed. The pinnacles are separated by chasms and pits that equal them in width. The chasms reach the bottom of the bed. They are filled by a carbonate mudstone lithologically discrete from that of the pinnacles; in the lowermost portion of several of them there are void fillings of blocky spar. By analogy with an instance described in LINDSTRÖM 1979b, the chasms are interpreted as channels for the percolation of gas escaping from the underlying argillite.

The lithology underlying the first hardground is carbonate mudstone consisting principally of »ant-eggs« 5–10 μm thick and 10–15 μm long. The biogenic content is less than 1 %. Fossil fragments are coated by palisade-like fibrous calcite. The yellow-stained zone is about 5 mm thick at the top of the pinnacles and fades out about 8 mm above the base of the limestone bed. It consists of the described lithology with goethitic matrix. Below it is a bleached zone a couple of mm thick, below which there follows red limestone. Both the latter and the bleached zone are again the same lithology; however, they are cemented by calcite.

The second hardground can be identified on patches of limestone adhering to the first. The lithology of the limestone remnants on which the second hardground developed is carbonate mudstone consisting essentially of 10–15 μm thick and 20–40 μm long »ant-eggs«; thus it is appreciably coarser than the first lithology. The second hardground, like the first, has a thick yellow zone with goethitic matrix. Where it meets the first hardground the latter is not in any way effected (Pl. 2, Fig. 8, 9). This indicates that the first hardground was cemented and practically impermeable when the second formed. In places the hardgrounds have a skin of pale, calcite cemented »ant-egg spar« (AES) external to the goethitic zone. This skin apparently represents a brief stage of reduction of the goethitic cement, before formation of the lithology that follows next.

The next lithology, terminated by the third hardground, consists of microspar with crystal sizes about 5–10 μm. It contains less than 5% of irregularly shaped, angular calcite fragments, 20–50 μm in cross section, that cannot readily be described as cement. Such particles, included in glauconite matrix, were found in the Yxhult sample as well (Pl. 2, Fig. 5).

In addition, there are less than 5% of recognizable biogenic fragments, as well as scattered »ant-eggs«. Like the preceding lithology, this one has a restricted occurrence as patches adhering to the first hardground. The upper limit of these patches approximately corresponds to the summit level of the pinnacles of the first hardground. The yellow stained zone of the third hardground is 2–3 mm thick. Below it there is a bleached zone. The basal portion of the third lithology is reddish and follows abruptly on either of the preceding, yellow-stained hardgrounds.

The fourth generation of carbonate mudstone is a micrite to microspar with crystal sizes mostly below 5 μm. It contains less than 5% biogenic components, some of which have a coating of columnar calcite, as well as minor amounts of angular calcite fragments like those referred to in connection with the previous lithology. This carbonate mudstone reaches several millimetres above the preceding hardgrounds. In several cases it plugs the channels leading to the base of the beds; in other cases it reaches down the walls of these channels, thereby restricting their width. It bears a narrow but intensely yellow stained zone along the irregular hardground (the fourth in order) that forms its top. However, most of the lithology is brownish red.

The lithology of the layer terminated by the fifth hardground is the same as the preceding. The fifth hardground is situated about 2 cm from the top of the bed. It is continuous but for a big number of 2–5 cm wide pits, some of which continue to the base of the bed along those of the preexisting channels that were left at stage five. The last of these channels apparently were not closed until after stage seven. It is an open question whether they are to some extent of organic origin, or not.

The sixth and seventh stages of carbonate mudstone sedimentation, cementation, and subsequent formation of hardgrounds, are represented by AES with »ant-eggs« in the size range 5–10 μm thick and 10–30 μm long. This lithology contains less than 10% biogenic fragments, mostly overgrown with columnar calcite, and less than 10% of small, angular calcite fragments. The sixth discontinuity surface is not very prominent. The seventh, situated near the top of the bed, has numerous irregular, 2–5 mm wide, bore-like channels.

The observations described above indicate that the morphologic and diagenetic evolution of each hardground was completed before the sedimentary and diagenetic events leading to formation of the next hardground: The morphology and mineralization of parts of a hardground that became exposed during formation of younger hardgrounds do not differ perceptibly from those parts remaining under sedimentary cover.

The goethite cement of the hardgrounds is a problem because fine-grained goethite in the presence of water is unstable relative to hematite at all temperatures relevant in geological contexts (BERNER 1969, LANGMUIR 1971).

The bleached zone separating the goethite from the hematic pigmented deeper zone of each limestone generation suggests that the hardgrounds were subjected to reducing conditions before the goethite matrix was formed. In all probality, the goethite formed by oxidation of pyrite. In view of the instability of goethite it is a reasonable first assumption that this took place in geologically recent time. However, this assumption implies that the hardground crusts remained pyritic during prolonged and repeated contact with oxidizing zones in the early Ordovician (goethite cemented hardgrounds invariably are directly covered by at least one generation of hematite pigmented limestone). Observations commented upon above indicate that the hardgrounds were scarcely modified once they had formed. Thus, the goethite probably is coeval with the hardgrounds, and its preservation must be due to exceptionally good protection from later diagenetic influence. The findings of MOUGIN & al. (1974) indicate that the dehydration of goethite to hematite might be stopped if the micro-environment is sufficiently well sealed off.

In places, the walls of channels between the base and top of the limestone bed carry small, stromatolite-like structures that are 0.5–5 mm (Pl. 3, Fig. 3) thick. They consist of 20–100 μm thick lamellae of hematite, goethite and either blocky or radial calcite. Baryte crystals may permeate several lamellae. In some cases these structures appear to block the channel in which they have grown. It is significant that the structures always grew away from the host hardground. The mineralization and morphology of the latter appear to be unaffected. Owing to their curvature, lamellae consisting of blocky (or, frequently, monocrystalline) calcite may mimic biogenic fragments in thin section. Radial calcite frequently forms the outermost lamella. The calcite is interpreted as filling spaces opened by dehydration skrinkage. On the basis of experience of numerous instances of similar structures in different parts of the orthoceratite limestone succession of Sweden, these structures are interpreted as results of oxidation of pyrite within the semi-consolidated sediment. PÕLMA (letter, 1978) has reached a similar conclusion for the same kind of structures encountered in the same facies in Estonia. Oxidation of pyrite in water generated sulphate ions and iron oxide hydrate. Barium was obviously present in the pore water of the less well cemented sediment phase into which the structures grew; when encountering sulphate ions it must form baryte, since the solubility of barium sulphate is extremely low. The puzzle appears to be that sulphate ions should have been present in the pore water itself, since this was sufficiently oxygenated to promote oxidation of pyrite. Conceivably, the reactions took place at the boundary between oxygenated pore water, with sulphate ions, from above, and anoxic pore water, bringing barium, from below.

»Blommiga Bladet«: extensive hardground complex (basal Volkhovian).

BOHLIN (1949, p. 534) briefly described a bed at the base of the »Limbata Limestone« (mid-Arenigian, Volkhovian) of northern Öland under the quarrymen's name »Blommiga Bladet« (»Flowery Sheet«). On northern Öland the bed earned its name by its vivid colours (red, yellow, and shades of green).

By conodont stratigraphy, this bed is at the base of the recorded range of *Baltoniodus triangularis* and at the top of the continuous range of *Oistodus lanceolatus*. Its base can be taken to mark the boundary between the Latorpian and Volkhovian Stages of the Baltoscandian Arenigian (see, for instance, MÄNNIL 1966).

The most important features of this hardground are its smooth upper surface and the abundant sac- or amphora- like borings by which it is penetrated. JAANUSSON (1961, p. 226–227) refers to the great horizontal extent (400 km) of this surface east of the Baltic; the occurrence on northern Öland increases the east-west extent by another 400 km. In fact, it appears that before post-Ordovician erosion »Blommiga Bladet« covered more than 1000 km in the east-west, and at least 500 km in the north-south, direction.

I have studied »Blommiga Bladet« at Horns Udde, northern Öland (were it is 2.7 m above the base of the Ordovician), the Cementa quarry of Degerhamn (Möckleby), southern Öland (1,75 m above contact between alum shale and grey glauconitic limestone), Borghamns Kalkstensbrott, Borghamn (see LINDSTRÖM 1978) (base of continuous limestone section, resting on lower *Didymograptus* Shale), Bjällum, Västergötland (LINDSTRÖM 1979b) (0,5 m above base of Ordovician, in deserted quarry to the west of the road), Yxhult, Närke (locality referred to by LINDSTRÖM, 1955 and TJERNVIK, 1956) (3.5–4.0 m above base of Ordovician), and Sjurberg, Dalarna (locality referred to by THORSLUND & JAANUSSON 1960) (locally derived boulders at lower part of shore section; dated by means of conodonts). The hardground complex in the lowermost Volkhovian of Kinnekulle, described in the preceding section, is close to »Blommiga Bladet« in stratigraphic age.

The hardground complex comprises one, two, or (rarely) three smooth surfaces as well as several irregular ones. Its total thickness as a rule is between 10 cm and 20 cm.

The smooth surfaces cut across fossils and other preexisting structures. Pl. 1, Fig. 7, shows a smooth hardground cutting through an inclined fragment of a limestone bed. The smooth hardgrounds have very characteristic borings (BOHLIN 1949, ORVIKU 1960, Fig. 4 & 5, JAANUSSON 1961, LINDSTRÖM 1963). The borings commonly are about 5 cm deep and 1–2 cm wide in their lower portions. They get somewhat narrower toward the top. Borings consistently about 3 cm deep and 0.7 cm wide can still be recognized as belonging to this category. The typical cross section of the borings is nearly circular. To judge from Fig. 4 of ORVIKU, 1960, there may be as many as 40 borings in 100 cm^2; my material suggests about 20 borings/100 cm^2 to be relatively close spacing. In many cases there are tens of centimetres between the borings.

The pits thus described are true borings i. e., they penetrate matter that was indurated when they formed.

They cut through trilobite remains as well as old hardgrounds encountered within the sediment. However, the borers did not decline an easy task: old borings, filled with sediment (that presumably was somewhat softer than the surrounding rock) frequently were reexcavated.

Commonly, though by no means universally, there are horizontal tubes, about 4 mm wide, that open into the pits. The tubes are somewhat irregular and sinuous. They may branch and anastomose. The pits may be interconnected by a system of such tubes. In several cases it was observed that pits extended downwards from a sub-hardground tube, rather than from the hardground itself. Other pits, connected to the same network, opened on the hardground.

The horizontal tubes appear to have formed where the sediment was less indurated. Two observations support this interpretation. Tubes commonly extend along the upper surface of earlier buried hardgrounds. They usually do not penetrate these hardgrounds although pits with which they are connected may do so. Furthermore, the levels at which the tubes occur appear somewhat marly or show other signs of heterogeneity. Where the limestone gets massive, there are no tubes. Commonly, there is a tube network several millimetres below a hardground. This may suggest that the uppermost millimetres of the sediment were first to be indurated.

At Bjällum, the substratum of »Blommiga Bladet« is a grey limestone that is very rich in glauconite grains. The hardground is covered by a thin sheet of pyrite that extends down the walls of the borings. The pits are filled by light grey lime mudstone belonging to the overlying bed. At Yxhult, the setting of »Blommiga Bladet« likewise is grey limestone, without glauconite grains, however. A glauconite skin covers the surface and the walls of the pits. Relatively little pyrite is involved. At Sjurberg the limestone matrix is dark brownish red. The hardground has a 2 mm thick, yellow zone. Similar goethitic zones surround the borings of which there are at least two generations. Both generations of borings have glauconite covered walls and are filled with brownish red lime mudstone. In the earliest generation, the filling is cut by the hardground, and its uppermost part is coloured yellow along with the latter. The red filling of the second generation continues upward through the hardground.

At the appropriate stratigraphic level at Degerhamn there are within 15 cm three surfaces that more or less fit the description of »Blommiga Bladet«. The lowermost is situated on top of a 6 cm thick bed the basal portion of which consists of grey marlstone with schlieren of light brownish grey carbonate mudstone. The streaks of marl get more rare upwards; the upper half of the bed consists of light brownish grey carbonate mudstone and reddish brown trilobite wackestone, the latter irregularly distributed within the mudstone. The upper surface of this bed is perfectly smooth. From it there descend lobate pockets, the walls of which are coated with glauconite (Pl. 1, Fig. 6). Where the pockets reach the basal part of the bed they show evidence of vertical shortening and lateral deflection. The limestone adjacent to the pockets has a more or less developed zone of pyrite enrichment. This zone extends into the surrounding limestone along small fractures departing from the pockets.

The next 3 cm of the succession consist of a basal layer of grey mudstone and 3 layers of grey trilobite packstone to wackestone, each topped by a discontinuity surface with a warty appearance. The lowermost two beds at two discrete phases provided filling material for the pockets of the underlying bed. Part of the basal mudstone layer was lifted from the smooth hardground before lithification of the first wackestone layer, which invaded the rupture; a thin crust of microcrystalline calcite with radial and laminar structure was added on the lower side of the lifted layer. There follows a 4 cm thick layer of light brownish grey mudstone, with schlieren of marl in its lower part. The top is a nearly smooth hardground with a few irregular borings. The walls of the borings are coated with glauconite; the adjacent limestone is heavily pyritized.

Next comes a 0.5–2 cm thick, light grey mudstone that extends into the underlying borings and has a jagged discontinuity surface at its top. Above it there is a light brownish grey mudstone. 2.5 cm above the nearly smooth hardground there is a further irregular discontinuity surface. The next bed is 3 cm thick. It consists of grey trilobite wackestone. It contains sac-like borings, as much as 5 cm deep and provided with a filling of light yellowish grey mudstone.

»Blommiga Bladet« at Horns Udde was briefly described by LINDSTRÖM, 1963. It consists essentially of red carbonate mudstone to trilobite wackestone. There are two smooth hardgrounds separated by about 10 cm of limestone with 1–4 irregular discontinuity surfaces. The upper hardground has the greatest number of borings. Most of these end above the lower smooth surface, but a few penetrate the whole layer. Borings extending below the lowermost hardground may end in a layer of light greenish grey marl that forms the substratum of »Blommiga Bladet«. The borings are filled with argillaceous carbonate mudstone. In the lower part of the borings the filling is light greenish grey; in the upper part it commonly is dark reddish brown. The walls of the borings are partly covered by glauconite. The limestone adjacent of the upper part of the borings is yellow. The filling of the borings contains small, spar filled vugs. There is hardly any megascopic pyrite.

As described by LINDSTRÖM, 1978, the structure of »Blommiga Bladet« at Borgham is complicated by slumping (Pl. 1, Fig. 7). The rock is a carbonate mudstone, in its lower part with a great deal of glauconite grains and quartz and feldspar sand. One can distinguish 8 cycles consisting of sedimentation, lithification, in some cases followed by slumping, and development of hardground. Within a few tens of metres the dominant colour changes between dark brownish red and light reddish grey. Fillings of borings are light greenish grey. Hardgrounds and borings have a thin glauconitic skin. Under the hardgrounds and adjacent to the borings there is a yellow zone that is a few millimetres thick. Pyrite is rare. A smooth hardground with sac-like borings cuts through diverse kinds of preexisting structures. Where these structures contain displaced older hardgrounds, the yellow zone connected with the smooth, crosscutting hardground is thin and discontinuous, evidently because chemical reactions involving goethitization were hampered by the greater amount of preexisting cement in the displaced slabs.

Thin sections of »Blommiga Bladet« at Horns Udde reveal several interesting features. The lithology of the upper bored layer does not vary much, depite striking differences in colour: it is a carbonate mudstone consisting mainly of microspar, with crystals of about 5 μm. The structure is rendered somewhat porphyritic by larger, irregular, monocrystalline calcite particles in the size range 20–30 μm (compare with the Hällekis hardgrounds, p. 13). Trilobite fragments are from a few tens of microns to several centimetres. Echinoderm fragments and small brachiopod valves are very subordinate. Away from the borings this lithology has a strong, hematitic stain. Close to the borings there is a zone of goethitic stain. This zone, a couple of millimetres thick, either passes directly into the hematite stained surroundings or is separated from these by a distinct, nonstained zone. A zone without goethitic stain may also be preserved along the wall of the borings. In places, minor concentrations of hematite may occur within this zone. Elsewhere, the goethite stain reaches the borings. A zone of glauconite impregnation, a few tens of μm thick, may coat the borings. However, this zone may be disrupted, in which case fragments of it may occur as intraclasts. The borings are filled by single-crystal calcite particles and fossil fragments, the latter mostly coated with radial calcite, in an argillitic, hematic, or glauconitic matrix. The monocrystalline calcite particles are size graded, with a size range of 5–30 μm in the upper part and 10–100 μm in the lower part. Their shape is rounded rather than angular.

Skeletal fragments in the glauconitic zone are bodily glauconitized. The glauconitization of individual particles may extend as much as a millimetre away from the glauconite crust. In the goethitic zone, preferential goethite impregnation of trilobite fragments is a common feature. The impregnation appears as a persistent change of colour. Other changes of optical properties are not evident in most goethite impregnated shells. Certain shells are glauconitized adjacent to the boring and goethitized farther away from it (Pl. 3, Fig. 8).

In the absence of a glauconitic zone, certain skeletal fragments project from the surrounding lithology into the boring. Such fragments may develop a thick coat of radial calcite only within the boring.

The goethitic zone surrounding the borings of Horns Udde corresponds to a pyritic zone in the otherwise closely similar instance found at Degerhamn. This suggests that goethite formed through the oxidation of pyrite. Another indication in the same direction is that iron oxide is generally concentrated around biogenic fragments, in particular on the lower side, and within skeletal particles, for instance in echinoderm porosities and in micro-borings. These environments, for which poor oxygenation is rather to be expected, are plausible for the formation of sulphide but certainly not for primary concentrations of iron oxide.

With these observations and inferences in mind, the following sequence of events can be reconstructed for »Blommiga Bladet« as exemplified by the upper part of this layer at the Horns Udde outcrop:

1. Deposition of calcite mud, largely allochthonous and partly biogenic.
2. Sulphide precipitation within the mud.
3. Oxidation of sulphide resulting in goethite and sulphate; the latter soluble.
4. Ageing of goethite to hematite.
5. Partial cementation, probably by Mg poor calcite (by analogy with instances discussed on p. 19–20).
6. Chemical (and physical?) erosion leading to smooth surface of hardground. There is no indication that any stage of this process took place at, or near, sea-level. A stable low-energy environment is indicated (see LINDSTRÖM, 1963).
7. Attack by borers.
8. Reducing conditions in sediment surrounding the borings.
9. Formation of a sulphide zone round the borings.
10. Oxidation of sulphide to goethite, accompanied by further cementation. Limestone bed essentially impermeable from now on.
11. Goethite closest to borings partly reduced, with bleaching as a result; some of the goethite close to the borings aged to hematite.
12. Glauconite crust forms in the (still empty) borings. The environment is slightly acid, which promotes replacement of skeletal fragments by glauconite.
13. Borings filled with calcite mud and silt, mixed with argillaceous material. Glauconite crust eroded during this process.
14. Formation of minor amounts of sulphide within the borings; formation of calcite cement.
15. Oxidation of sulphide in the upper part of borings.

The reoccupation of certain borings by a second generation of borers is not taken into account in this scheme; it evidently occurred either as a part of a more complex event 13 or as separate events between 14 and 15.

»Blodläget«: surfaces with hematitic warts (Volkhovian, northern Öland).

BOHLIN (1949) described »Blodläget« (»Bloody Layer«) as a 12 cm thick bed with three thin layers with warts of hematite. According to him it occurs in the »*Limbata* Limestone« (Volkhovian) over a distance of 70 km in northern Öland

(BOHLIN & JAANUSSON 1955, p. 120). For a section at Haget 10 km N of Horns Udde, BOHLIN (1949, p. 534) reports that »Blodläget« occurs about 2.3 m above »Blommiga Bladet«. The same is true for Horns Udde.

»Blodläget« in the narrow sense, defined by BOHLIN, is the lowermost of several beds with a combination of distinguishing features: they consist of light reddish brown limestone; they have irregular hardgrounds with a strong goethitic stain; and they contain spectacular concentrations of hematite, frequently in the shape of warts with horizontal dimensions of 5–50 mm and thicknesses of 1–10 mm (Pl. 1, Figs. 8, 9). Beds with these features occur within a sequence that is about 30 cm thick at Horns Udde and 75 cm thick at the coastal cliffs 6 km farther north. They are here collectively referred to as »Blodläget«.

»Blodläget« forms the basal part of the conodont zone of *Paroistodus originalis* as defined by LINDSTRÖM (1971) and LÖFGREN (1978).

The megafossil fauna is fairly monotonous. Certain discontinuity surfaces are strewn with *Megistaspis* pygidia, convex side upward, about 6 cm in size. Other surfaces contain an abundance of orthocone cephalopods with the long axis in horizontal but otherwise random directions. The thickness of these horizontal shells is in the range 1–4 cm. On the other hand, vertically oriented body chambers, about 6 cm across, are fairly common (compare REYMENT 1970). As noted by REYMENT (1958, p. 122), orthocone cephalopod shells of endoceroid type tent to float vertically, with the apex upwards. If buoyancy was reduced by (for instance, biogenic) punctation of a few proximal chambers, the shells might have sunk and stuck vertically, with the body chamber in the bottom mud. In very quiet water, shells might have been left standing until the attachment to the body chamber was broken by chemical (and/or biological) processes. That very quiet conditions are not out of the question is indicated by the preservation of other delicate structures on the Early Ordovician sea-bed (LINDSTRÖM, 1963).

The lithology of the »Blodläget« beds is skeletal wackestone to packstone. Polished sections and thin sections show hardgrounds at vertical distances of 5–15 mm. The hardground morphology typically consists of funnel-shaped pits spaced at 20–40 mm and separated by irregularly but rather smoothly rounded knobs. The pits are 10–20 mm deep, and tapering to a width of about 3 mm. Their walls may have a thin zone of glauconitic impregnation; for the rest, most hardgrounds are impregnated with goethite.

The sediment between the hardgrounds is graded. Immediately above a hardground there follows packstone. In not too deeply corroded beds this passes upwards into wackestone in which the skeletal particles are separated by micrite to fine microspar. The skeletal components, in order of decreasing frequency, are fragments of trilobites, echinoderms, and brachiopods, most of which are of sand grade. The cement of the packstone is sparry; it is suggested that the original porosity of the corresponding, basal part of the beds was relatively high.

The goethite occurs as a yellow hue in microspar, certain blocky cement spar, and the interior of many trilobite and echinoderm fragments. This hue is omnipresent in a 0,5–2 mm thick zone immediately underlying yellow hardgrounds; however, skeletal fragments with a yellow hue also occur among clear and well-preserved fragments within the beds. This might indicate some slight differences in the provenance of the fragments.

Most hematite occurs in the packstone. In thin sections it appears as schlieren and laminae of hematite matrix and as minor concentrations at skeletal fragments. In the latter case it either coats the fragments or fills cavities like borings, pores in the interior of echinoderm sclerites, and the interior of gastropod larval shells. Unlike goethite, hematite does not form a penetrative hue in trilobite fragments and cement crystals.

Goethite apparently was preserved only where protected by calcite fabrics that became relatively impenetrable at an early stage of diagenesis. Such protected environments were, for instance, the interior of early calcite cement crystals, calcite mud with initially narrow pore spaces that were closed by early cementation, and the interior of trilobite exoskeletal fragments. In less protected environments the goethite aged to hematite.

The hematitic warts appear in thin sections as schlieren and laminae of hematite matrix. They occur above upward projections of underlying hardgrounds. In many cases they show distinct stromatolite-like lamination (Pl. 3, Fig. 1). The laminae are parallel to the substratum; hence they are convex upward. Laterally and downwards they fade away in the surrounding packstone. Hence, they do not mark boundary surfaces of deposition. They are regarded as effects of rhythmic precipitation within already existing deposits.

The mode of occurrence of hematite and goethite in the fossils suggests that the iron was at first trapped as sulphide. This appears to be the most plausible general manner of fixation of major quantities of iron in the cases described here. There are numerous obvious reasons why Recent ferromanganese nodules (otherwise superficially similar) are irrelevant in this context, the first and foremost being that the rocks under discussion contain but trace amounts of manganese.

In »Blodläget« at Gillberga (sample number Gi 8a) the hematitic cap abouve a hardground protuberance contains a great number of concentric laminae consisting alternately of hematite and calcite cement. The calcite laminae are the thinner ones, except for a lamina of radial calcite at the outer boundary of the hematite cap. They are interpreted as fills of shrinkage cracks. Such cracks would form where goethite converts to hematite within a rigid (cemented, yet still somewhat porous) frame. On the other hand, expansion, with some reorientation of surrounding sedimentary fabric, is to be expected in the preceding stages: growth of pyritic laminae could push adjacent sediment aside, and oxidation of pyrite with retention of the iron as goethite must do so. The expected orientation of tabular particles parallel to ferrugineous laminae is generally present in thin sections from different localities.

The repetitive arrangement of ferrugineous precipitate in the »warts« could be explained according to at least two different models. According to the first, cementation proceeded from the base of the bioclastic sediment. Concomitant sulphide precipitation took place no deeper than the cementation front. At stages when this front came to a standstill, it became the locus of formation of a distinct sulphide lamina. Vacillating redox conditions might have led to oxidation of this lamina even before it was overtaken by renewed advance of the cementation front. This succession of events was then repeated a number of times. Another model, maybe less plausible than the first, is that sulphide precipitation took place at a certain depth below the sediment surface. As new sediment was added, the level of sulphide precipitation moved upwards. Sulphide laminae could have time to form at stages of particularly slow sedimentation. Oxidation took place either before or after cementation had begun.

B a r y t e forms part of the surface of certain hardground protuberances. The baryte crystals may be at least 3 mm long. Their shape is amoeboid: they enclose many carbonate grains and form networks and small enclaves in the surrounding carbonate sediment (Pl. 3, Fig. 2). Echinoderm ossicles are partly replaced by baryte. Much of the baryte is colourless; however, parts of certain crystals have a yellow goethite hue. It is suggested that the baryte formed at a stage when most of the hardground was below the oxidizing zone in which sulphate would form through the destruction of sulphide. Only the higher parts of protuberances rose into this zone. Under these conditions barium could be mobile in the pore water of the deeper level; once it entered the level of oxidation it was precipitated as sulphate. The size of the baryte crystals indicates that this was a slow process with relatively few centers of nucleation.

Discussion

Stratigraphic considerations

The hardgrounds discussed above were chosen as illustrations of certain diagenetic features. They are in several respects representative, in other respects (morphology and amount of enrichment of oxidized iron) special; by any means they are a small sample. The Billingen Substage of the Latorpian (Lower Arenigian) of Horns Udde alone contains at least 40 hardgrounds. The Substage is 2 m thick at that locality. At Yxhult the entire Latorpian contains at least 40 hardgrounds within a thickness of about 3.2 m.

As shown above, the formation of a hardground involved several diagenetic steps. This may have required a great deal of time. On the other hand, the sedimentation of the content of each limestone bed may have been a geologically fast process (see below); it is probable that the hardgrounds represent the major portion of the total time span involved in the formation of the orthoceratite limestone. The Billingen Substage represents probably not less than 1 and certainly not more than 5 million years of Ordovician time. This makes 25 000–125 000 years available for the formation of an average hardground at Horns Udde.

Certain hardgrounds might represent longer time intervals than the average. Important stratigraphic boundaries are to be found at hardgrounds. These boundaries are defined by first appearance, ultimate disappearance, and discontinties in the occurrence of leading components of the faunal association. Because other ecologic indicators suggest a continuum without great environmental evolution within the early and middle Arenigian, abrupt changes in the faunal composition at the species level may be suspected to be to some extent due to omission of a significant part of the geologic record (this does not discount the application of modern theories on evolutionary pattern as another component of the explanation of abrupt faunal changes at the species level).

»Blommiga Bladet« at the base of the Volkhovian Stage provides a good illustration of this argument. Important changes in the megistaspid megafauna and the conodont microfauna are documented to occur at the base of this complex of hardgrounds (TJERNVIK 1956, LINDSTRÖM 1971). In Scania and parts of Västergötland a change from relatively rapid deposition of graptolite carrying argillaceous sediment (the order of 1–10 m for the Latorpian Stage) to the orthoceratite limestone facies took place while the »Blommiga Bladet« complex was forming or shortly thereafter; at Kinnekulle (Västergötland) the base of the orthoceratite limestone contains spectacular hardgrounds, as described above. At Borghamn (Östergötland) the change from argillaceous to calcareous facies occurred just before formation of »Blommiga Bladet«. It is suggested that there was a causal relation between this change and the prolonged standstills of sedimentation indicated by the hardgrounds.

»Blodläget«, with a hardground frequency of ca. 1 per 10 mm vertical section, occurs at an important conodont stratigraphic boundary within the Volkhovian (equivalent to the boundary between the Saka, BIIα, and Telinõmme, BIIβ, Beds of Estonia; see MÄNNIL 1966).

It might be significant that our thin sections of »Blodläget« contain a few instances of trilobite fragments bored by thallophytes (cf. HESSLAND, 1949). These are the oldest Swedish instances of this category of borings known to me. The borings get more frequent in the lower Kundan (uppermost Arenigian) of northern Öland. They are absent in higher parts of the Lower Ordovician. Although the thallophyte-borings so far found within »Blodläget« appear to be of fungal rather than algal origin (the differences are discussed in BROMLEY 1970), they might nevertheless signal a trend towards reduced water depth. This trend might have been accompanied by a stage of increased frequency of hardground formation owing to increased bioproductivity, reactivity within the sediment, and rates of cementation.

Diagenesis of iron compounds

The glauconite cannot be treated in any great detail here. It is discussed insofar as it forms crusts at hardgrounds. According to light optic studies of thin sections it is a normal glauconite. It is being investigated by Dr. W. Vortisch, Marburg. In some cases, referring the involved minerals of the illite group to glauconite is a simplification of the matter.

The preferential occurrence of glauconite crusts in the upper parts of certain dome structures, long exposed in the sea-water (LINDSTRÖM 1963), indicates certain factors of the genesis of crusts: time, and absence of sedimentary cover. It is generally agreed that glauconite forms under ambivalent redox conditions (literature review by KOHLER 1977). As a rule, these conditions are obtained through balancing a generally oxidizing outer environment by a somewhat reducing microenvironment.

It is difficult to visualize a reducing microenvironment at the contact surface between well oxygenated sea-water and sediment, unless this surface was coated by a film of, for instance, organic material (a bacterial film?) (see BROMLEY 1965 as cited by BATHURST, 1971, p. 411). However, on a well oxygenated sea-bed such a film would have fallen prey to browsers; there was time enough for that. The fact is that the glauconitic crusts have not yielded any definite traces of browsing. It is possible that oxygen was not the factor that limited higher life on the sea-bed. With this caution, one might consider the hypothesis that the sea-bed was poorly enough oxygenated for sufficiently long periods that glauconite crusts could form in contact with sea-water.

The elemental constituents of the glauconite crusts could have come

1) from the underlying sediment,
2) from the sea-water, or
3) from particles (basaltic volcanic dust?) trapped by a (bacterial?) film on the surface.

Alternative 2 is least probable, since aluminium and iron are very little soluble in sea-water.

Alternative 3 is not implausible. The degradation of basaltic tephra could yield the iron, aluminium, magnesium, and silicon necessary for the formation of glauconite; potassium could be provided from the sea-water solution. Alternative 1 is at least equally plausible, since aluminium, iron, and silicon would be more soluble within the sediment (relatively high pH, strongly reducing conditions, lowered sulphate concentration) than at the sediment/sea-water interface. Hence, precipitation of dissolved phases could occur at the interface.

Except where glauconite is concerned, sulphide, principally occurring as pyrite, is taken to represent the first stage of fixation of iron. There is no evidence that the sulphide formed on the sediment surface. Even at »Blommiga Bladet« of the Bjällum section (p. 14), the pyrite crust could have formed after deposition of the succeeding layer.

Sedimentary pyrite normally forms in three main steps (BERNER, 1970):

1. Bacterial, anaerobic reduction of sulphate to sulphide ions. The bacterial activity requires organic nourishment.

2. Precipitation of iron monosulphide; the ferrous iron is provided by the sediment.
3. Oxidation of iron monosulphide to bisulphide by elemental sulphur; the sulphur originates through oxidation of sulphide ions and requires interaction between anoxic sulphide solution and oxygenated water.

The distribution of preserved pyrite in the investigated samples suggests that the major part of the reactions took place within a narrow zone of a few millimetres below the sediment surface. This narrow restriction of the main sulphide zone may have been caused by low diffusivity owing to incipient cementation. The elemental sulphur necessary for pyrite formation could be provided only if the pore water adjacent to the sediment surface was to some extent oxygenated.

G o e t h i t e would form by oxidation of pyrite after the content of organic carbon within the sediment was depleted. Some of the elemental sulphur liberated by this reaction might have remained available for subsequent formation of pyrite.

There are three alternatives for the fate of the goethite within the sediment:

1) It could be subjected to a new phase of reduction
2) It could be preserved as such, and
3) It could convert to hematite.

The first two alternatives require special conditions.

Because the presence of major amounts of goethite indicates that the prerequisites for anaerobic conditions within the sediment had ceased to apply, a new phase of reduction must have come from without, presumably from a layer of new sediment that might or might not be preserved. This is taken to be the condition under which hardgrounds were subjected to bleaching and renewed pyritization, inferred for instance on p. 15. The process could be enhanced by percolation of methane through the loose sediment cover.

The preservation of goethite appears possible only within microenvironments with extremely low late-diagenetic permeability, such as the interior of solid trilobite fragments (borings in trilobite fragments and pores in echinoderm fragments frequently contain pyrite, hematite, or glauconite, rarely goethite), the interior of cement crystals, the interior of neomorphic spar in mollusc shells, and dense microspar. The mode of occurrence of goethite in the Hällekis complex of hardgrounds (p. 13) testifies to the efficient closure of the porosities of the rock by successive phases of cementation.

Unless very well protected, the goethite normally is dehydrated to h e m a t i t e (LANGMUIR 1971). JAANUSSON (1973) and LÖFGREN (1978) appear to have been the last to comment on the role of hematite as a characteristic pigment in the orthoceratite limestones. JAANUSSON observed that the iron content of grey and red limestone beds of the same sequence appears to be the same. Apparently the iron was retained in the successive stages leading to hematite formation.

Indeed, the occurrence of hematite even on the microscopic scale suggests that it remains where iron had accumulated as sulphide. Hematite is particularly concentrated in endolithic microborings, the interior of echinoderm fragments, gastropod and cephalopod protoconchs, and trilobite spines, in short, microenvironments where one would expect sulphide precipitation to occur, and where sulphide is preserved in a great number of cases.

As noted above (p. 16), the formation of goethite after pyrite is accompanied by expansion, which leads to reorientation of tabular bioclastic components parallel to the expansion front. Where greater quantities of iron oxide are involved this process can create structures with a certain similarity to stromatolites, a resemblance that is enhanced where concentric shrinkage cracks, filled with calcite, developed as a consequence of dehydration to hematite.

The excellent preservation of the ferruginous phases is ascribed to absence of post-Early Paleozoic weathering in the investigated beds; weathered beds were removed by Quaternary land ices.

B a r y t e

Owing to the very low solubility product of barium sulphate (PUCHELT 1972), barium cannot be provided by sea-water solution. The baryte that has replaced calcium carbonate at certain hardgrounds must have been transported by pore water solution depleted in sulphate. At the hardgrounds barium ions met sulphate ions, which resulted in formation of baryte. The source of sulphate may be either sea water sulution or, presumably, oxidation of sulphide. Abundant inclusion of goethite pigment in some baryte crystals is evidence for oxidation of sulphide at the sites of baryte formation. The replacement of calcium carbonate by baryte may hypothetically be explained by the circumstance that the solubility gradient for baryte was negative as the hardground was closely approached, whereas that of calcite was positive, owing to decreasing alkalinity toward the sediment/sea-water interface (such conditions were analyzed by GOLDHABER & al., 1977; they probably were even more accentuated in the cases discussed here).

BJÖRLYKKE (1974) shows that barium occurs abundantly in certain Lower Ordovician beds in the Oslo area that is situated on the margin of the sedimentary realm characterized by orthoceratite limestone facies. HADDING (1938) refers to baryte from the Upper Cambrian and basal Ordovician of Sweden. The occurrences described by these authors are in black, sulphide-rich shale. WRUCKE & al. (1978) refer to the very common occurrence of barium in the Ordovician of western North America; the ultimate source of these occurrences according to their explanation may be oceanic volcanic activity. Since it is possible that much of the slowly deposited non-carbonate sediment of the Swedish Lower Ordovician is of volcanic origin (LINDSTRÖM 1974, 1979b) the volcanogenic explanation might be relevant in the cases discussed in this paper.

C a l c i t e c e m e n t a n d c e m e n t a t i o n

The only carbonate cement identified in the examined samples is magnesium-poor, non-ferroan calcite. It occurs mainly as

1) major, radial aggregates,
2) blocky mosaic,
3) syntaxial rim cement (sensu BATHURST 1958) including palisadelike fibrous cement on skeletal fragments, and
4) other fibrous calcite.

Microspar, of very common occurrence, is generally not regarded as cement (FOLK 1965, p. 21; BATHURST 1971, p. 475). However, its formation in the present case cannot be rigorously separated from pore-space filling. AES (p.11) is a variety of microspar.

The radial cement aggregates of the *Oepikodus evae* Zone of Horns Udde apparently formed in a non-cemented carbonate mud below a cemented hardground. Among the discussed cases this is the only one for which these conditions are likely. The case is a rare one in at least one further respect: calcite cement and pyrite are intergrown in such a manner as to show that they formed at the same time. Another instance of similar evidence is described by LINDSTRÖM (1979b).

On the other hand, much cement growth occurred under relatively oxidizing conditions: there appears to be no other explanation for the inclusion of great amounts of goethitic pigment in the calcite crystals.

It is not immediately evident why the calcareous mud below the hardground crust remained non-cemented for a long enough period to allow the aggregates to grow in a soft medium, or why oxidizing conditions could function so well below the hardground crust, an environment of established sulphide precipitation. A conjectural answer to these questions might be that oxygenated water, brought by burrowers (that retarded cementation by moving the sediment about) was frequently chased by methane erupting from underlying argillaceous beds (LINDSTRÖM 1979b). The percolation contributed to the mobility of the sediment and ensured a frequent recurrence of anaerobic conditions (compare also JÖRGENSEN 1976).

There are no indications that the calcite has recrystallized.

Blocky mosaic cement is met with as fillings of cavities and cracks. There are two categories of cavities, both of which occur rather sparsely in all samples. To the first belong closed cavities within fossils, such as ostracode carapaces. These are filled by a peripheral rim of fibrous calcite of uniform thickness and a central portion that consists of irregular, sub-equant crystals. Most cavities of the second category are less than 1 mm wide. Their roof either is a skeletal fragment with or without syntaxial rim cement, or consists of microspar with irregular morphology; the floor mostly is horizontally layered microspar. The spar filling of cavities as a rule is clear. In a few cases in »Blommiga Bladet« and »Blodläget« some crystals contain finely disseminated goethitic pigment; in one case a horizontal layer of goethitic pigment permeates calcite crystals at the base of a cavity.

Blocky cement as fracture filling occurs at many hardgrounds. In several cases it is demonstrably older than the hardgrounds because the latter cut across it. Pl. 2, Fig. 6, 7, shows an instance from a glauconitized hardground 1.4 m below »Blommiga Bladet« at Horns Udde (Sample Hun 8). The following succession of events is directly evident in this sample:

1) goethite precipitation (presumably preceded by sulphide impregnation),
2) opening of fracture,
3) commencing cementation by clear calcite,
4) glauconitization of a 0.1–0.5 mm thick superficial zone of the hardground; glauconite also filled the open spaces remaining in the fracture.

Syntaxial rim cement is of two different kinds: massive (mostly on echinoderm ossicles) and fibrous, or palisade-like (mostly on trilobite fragments). In those cases in which the pores of echinoderm ossicles are rich in iron oxide the massive rim cement tends to show oxidized portions. In other cases it is clear. The fibrous syntaxial rim cement extinguishes together with the portion of a trilobite fragment to which it is attached. It may contain great numbers of pyrite granules. In many cases it is stained by goethite. The principal evidence for its early formation is inclusion in glauconitic matrix.

The same evidence speaks for the early formation of »ant-eggs« (p. 12). »Ant-eggs« are single, oblong calcite crystals most of which are about 15–30 μm long and 1/3–2/3 as thick. Cross sections are sub-circular. A lithology dominated by »ant-eggs« is called ant-egg spar, or AES. In the terminology of FOLK (1965), who figured and described (fig. 12b and p. 39) a lithology that might be AES, this is a kind of microspar. AES could possibly be reworked palisade-like rim cement (p. 00). The occurrence of AES in the Hällekis hardground complex suggests size-sorting. The same hardgrounds furthermore yield evidence for the early formation of AES (p. 12). If the inclusions in glauconite show the original shape of rim cement crystals and »ant-eggs«, their mineralogy never was anything but calcite.

Ordinary microspar, consisting of subequant calcite crystals mostly smaller than 20 μm, forms over 50% of most orthoceratite limestones. AES dominated beds and some of the packstone of »Blodläget« contain smaller amounts of ordinary microspar. Owing to the small size of the crystals, their interiors and contacts cannot be adequately studied in thin section. Thus, it is impossible to distinguish between cement, neomorphism (if any), and original particles. The microspar fabric appears non-porous, and the larger of the microspar crystals appear to have straight boundaries against one another.

Many extensive hardgrounds consist of microspar with goethite pigment. Such hardgrounds are immediately overlain by lithologies without goethite but with either hematite or sulphide iron. If the goethite had formed at a late stage, its predecessor, which must have been sulphide (hematite is not hydrated to goethite) must either persistently have survived oxidation of the overlaying sediment, where this is red, or, with equal persistency, been prone to late oxidation that did not affect immediately overlying limestone. Since both alternatives are unlikely, the goethite is interpreted as coeval with hardground formation. The same must be inferred concerning the microspar because it was capable of preserving the goethite. If the arguments given above are correct, most cement formed in sea-water several millimetres to centimetres below the sediment surface (see also the following section on hardground morphology). The same applies to goethite stained neomorphic calcite for instance in mollusc shells. Carbonate precipitation within the sediment would have been furthered by the alkalinity gradient.

Aragonite and magnesian calcite cement are missing. The concentration of magnesium ions in modern sea water reduces rates of calcium carbonate cementation and prevents formation of magnesium-poor calcite (see for instance FOLK 1974 and BADIOZAMANI & al. 1977). This is the pièce de résistance against which one has to judge the strength of arguments for early calcite cement. If they are correct there are but two possibilities: either that the ocean contained much less magnesium ions in the Early Ordovician than at the present (see SANDBERG 1975), or that magnesium was selectively removed from the pore water of the uppermost few centimetres of the sea-bed sediment. The removal of magnesium from pore water could be effected by clay minerals; such a mechanism has been suggested in connection with the formation of microspar in the Ordovician Bromide Formation (LONGMAN 1977). However, LINDSTRÖM (1979b) and VORTISCH (1979) describe a Swedish Lower Ordovician occurrence of beidellitic clay that would n o t have formed in pore water that yielded magnesium ions. This clay is confined within early, magnesium-poor calcite cement. In this case the calcite is not poor in magnesium because magnesium ions we taken up by clay; there was not enough magnesium ions for the clay to take up. Perhaps the Early Ordovician sea as whole was poor in magnesium. In the early Paleozoic very great quantities of magnesium were trapped by dolomite formation in miogeoclinal sequences. If the sea water itself was relatively poor in magnesium ions this circumstance could have furthered calcite cementation. One untidy end of the argument is that the glauconite of the investigated facies contains normal quantities of magnesium. This could have come from degraded basalt glass, but there might be other possibilities, as well.

Morphology of hardgrounds

Most hardgrounds of the orthoceratite limestone consist of 5–20 mm high, irregularly convex protuberances separated by pits and grooves. A typical instance is shown by Pl. 2, Fig. 10. On a larger scale these hardgrounds are smoothly horizontal.

A few hardgrounds lack roughness of the indicated order and can be described as smooth. The pinnacled hardground complex of Hällekis is exceptional. Animal borings are a secondary feature shown by many hardgrounds.

Hardgrounds represent surfaces that move as fronts through a medium. Fronts tend to develop broad convexities in the direction of movement. Hardground topography, if formed primarily through solution from above, develops pits with rounded bottoms and flat-bottomed pans with rounded flanks; upward projections tend to be sharp-crested (READ & GROVER 1977). The hardgrounds of the orthoceratite limestone present the opposite to this topography. Because solution cannot have proceeded in the other direction (i. e., from below!), the moving front must have been one of c e m e n t a t i o n (see Fig. 4C). In other words, the limestone beds were cemented from below upwards, and the hardground topography was exposed when the non-cemented upper portion was eroded.

Smooth hardgrounds may be more difficult to explain than irregular ones. Excluding mechanical erosion (for which there is no evidence), I can imagine four different processes that might lead to a smooth hardground:

1) The hardground formed by cementation of the smooth surface of the sediment. This explanation probably requires that the degree of carbonate saturation of the sea water was higher when smooth surfaces formed than during the formation of »normal«, irregular hardgrounds.

2) The hardground formed by cementation of a bedding plane (such as the lower boundary of a volcanic ash layer), within the sequence. Overlying, non-cemented beds were removed by erosion.

3) The hardground formed under a layer of non-carbonate sediment the pore water of which was undersaturated with respect to calcite; pH decreased upwards. Because portions of the hardground dissolve faster the higher they project upward, this situation leads to smoothing of the topography (Fig. 4D, E).

4) The hardground formed by equal rates of dissolution at all points of an advancing front. The dissolution front in this case consists of adjoining spherical segments the curvature of which is reduced as the radii lengthen (Fig. 4F, G). The final result is a practically plane surface.

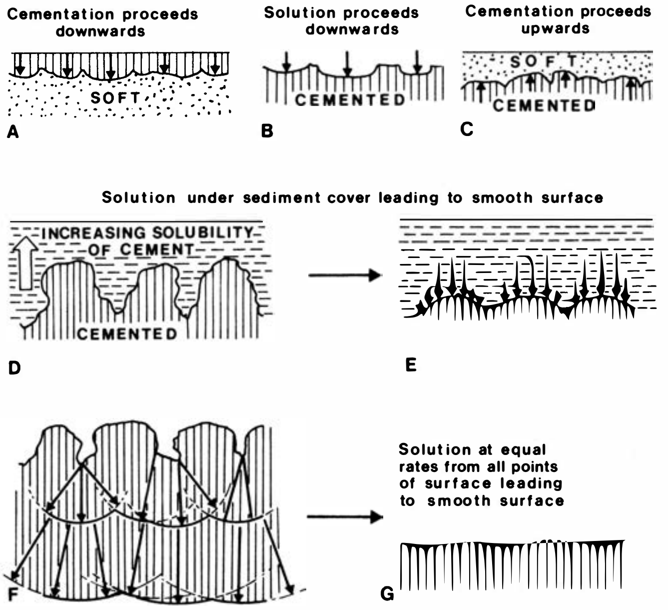

Fig. 4 : Dependence of hardground morphology on diverse factors. A : A lobate cementation front advances into the underlying sediment from a smooth hardground surface. B: A surface with sharp crests forms through the downward advance of a lobate solution front. C: The cementation front proceeds upward; a lobate hardground forms when the non-cemented sediment is removed. D, E: Hardground topography is smoothed if covered by sediment (dashed) in which cement solubility increases upward. F, G: Hardground topography is smoothed if a solution front proceeds downward at rates (radii) that are equal at all points.

In the cases studied by me the first two models appear to be contradicted by the circumstance that the smooth hardgrounds cut skeletal fragments. However, the implied erosion needs not to have been very deep-reaching, and the models might be valid in principle. The second model postulates a bed of contrasting lithology above the hardground, and one would expect to find such a bed preserved at least in a few rare places, yet this appears not to be the case. The third and fourth models suffer from a similar weakness: no intermediate stages in the reduction of hardground topography have been observed. The fourth model is the reverse of the first insofar as it involves great amounts of carbonate dissolution. Since the most important of the smooth hardgrounds occur in a complex (»Blommiga Bladet«) that bears evidence of stratigraphic condensation, model 4 is the stronger one on this point. The appearance of a set of smooth hardgrounds in the thin succession of beds of »Blommiga Bladet« is suggestive of the occurrence of volcanic ash layers (model 2); so is the very wide distribution of the set.

The borings will be discussed in the following section.

E c o l o g y

The fauna occurring in thin sections of the Arenigian orthoceratite limestones is dominated by trilobites, closely followed by echinoderms. Small articulate brachiopods form a minor portion of the fauna. Ostracodes and gastropod protoconchs are still less common. Conodonts and small acrotretid inarticulates can be identified in some thin sections. A few quantitative data on skeletal components of a stratigraphic section through Arenigian limestone in Sweden are given by LINDSTRÖM (1979a). PÕLMA (1972) published data for Arenigian (BI, BII) limestones of the easterly continuation of the same facies in Estonia. The biogenic composition of these limestones is the same as in Sweden (algae reported by PÕLMA 1972 are disavowed by him – letter, 1978 – as far as the Arenigian is concerned; it is a matter of laminated structures formed through decomposition of pyrite).

Megafossils are trilobites and cephalopods. The trilobite fauna is specialized; there are few species, most of which are asaphoid. Entire specimens are rare. What is mostly met with is pygidia. Since the hardgrounds lack body fossils of sessile benthos, there is no proof that any part of the megafossil fauna lived in the sedimentary environment.

Bore-like structures found at the hardgrounds are the main autochthonous indications of life. In view of the abundance and variety of such structures on certain younger hardgrounds (BROMLEY 1975) and the time available for exploitation of each hardground, the Lower Ordovician hardgrounds give an impoverished and monotonous impression. As a rule each hardground, unless barren, is characterized by a single kind of infaunal structures. Simple *Thalassinoides*-type structures are common on many hardgrounds. In some cases structures resembling *Thalassinoides* may have formed and been kept open by gas percolation.

The most characteristic borings are the abundant sac-like structures with interconnecting horizontal tubes characterizing »Blommiga Bladet«.

Contrary to *Thalassinoides*-like tubes that might be burrows formed before or during early stages of cementation (KENNEDY 1975, p. 390 points to this uncertainty with reference to the discussed instances) the »Blommiga Bladet« structures are proven borings.

Although abundant on transported trilobite fragments, microborings (ascribed to sponges by LINDSTRÖM, 1979a) do not occur on the hardgrounds. The preservation of an intact glauconite skin on numerous hardgrounds is regarded as further evidence against an active bottom fauna.

No body fossils of burrowing and boring fauna have been found. The question is, what the borers were after. It can be shown (LINDSTRÖM 1963) that the sea was quiet and certainly not very shallow. Nourishment on the sediment surface appears to have been sparse, as was animal life, and the sediment interior was but moderately exploited by the boring animals. Under these circumstances the need for protection by boring is not obvious. If nourishment was sought, this might not have been primarily from the bored sediment. Instead, it is suggested that borings occuring on smooth hardgrounds served as traps for sediment that was transported over the surface. In this way, what little nourishment that touched the seabed could be efficiently exploited. Furthermore, by digesting particulate matter the borers might have contributed to keeping the hardground free of sediment, thus maintaining the equilibrium of their environment.

Provenance of sediment

BOHLIN (1949, p. 559), dealing with orthoceratite limestone beds somewhat younger than those herein discussed, suggested that each bed might have been laid down by a storm. According to this hypothesis, catastrophic depositional events were separated by very long intervals without sedimentation. BOHLIN'S hypothesis has received very little attention from later authors. However, it has merits.

1. If the sediment was produced outside of the narrower areas within which it was permanently deposited and was brought into these areas by isolated physical events of short duration, there is no need to assume frequent oscillation between productive conditions and nondeposition and destruction of sediment in the same areas, as one must otherwise do in order to explain the frequent recurrence of corrosion surfaces.
2. The ecological conditions evidenced by the sediments are greatly different from those indicated by the hardgrounds, which are the only definitely autochthonous structures.
3. Microborings present on trilobite fragments (LINDSTRÖM 1979a) have not been observed on hardgrounds.
4. Asaphoid trilobites, which are the best represented megafossils, occur almost exclusively as pygidia. If the depositional areas were their habitat, one would expect to find greater numbers of thorax segments and portions of cephala.
5. Layers of orthoceratite limestone are characterized by different sizes of AES. AES is more or less well separated from bioclastics. The hardground complex of Hällekis offers particularly instructive instances of these principles that imply physical sorting – in other words, transport.
6. Size and density grading is a commonly occurring feature within the limestone beds.

The following hypothetical transport mechanisms can be considered:

a) Normal currents. This mechanism is unlikely because any trace of current lamination is lacking, and there are no directional structures.

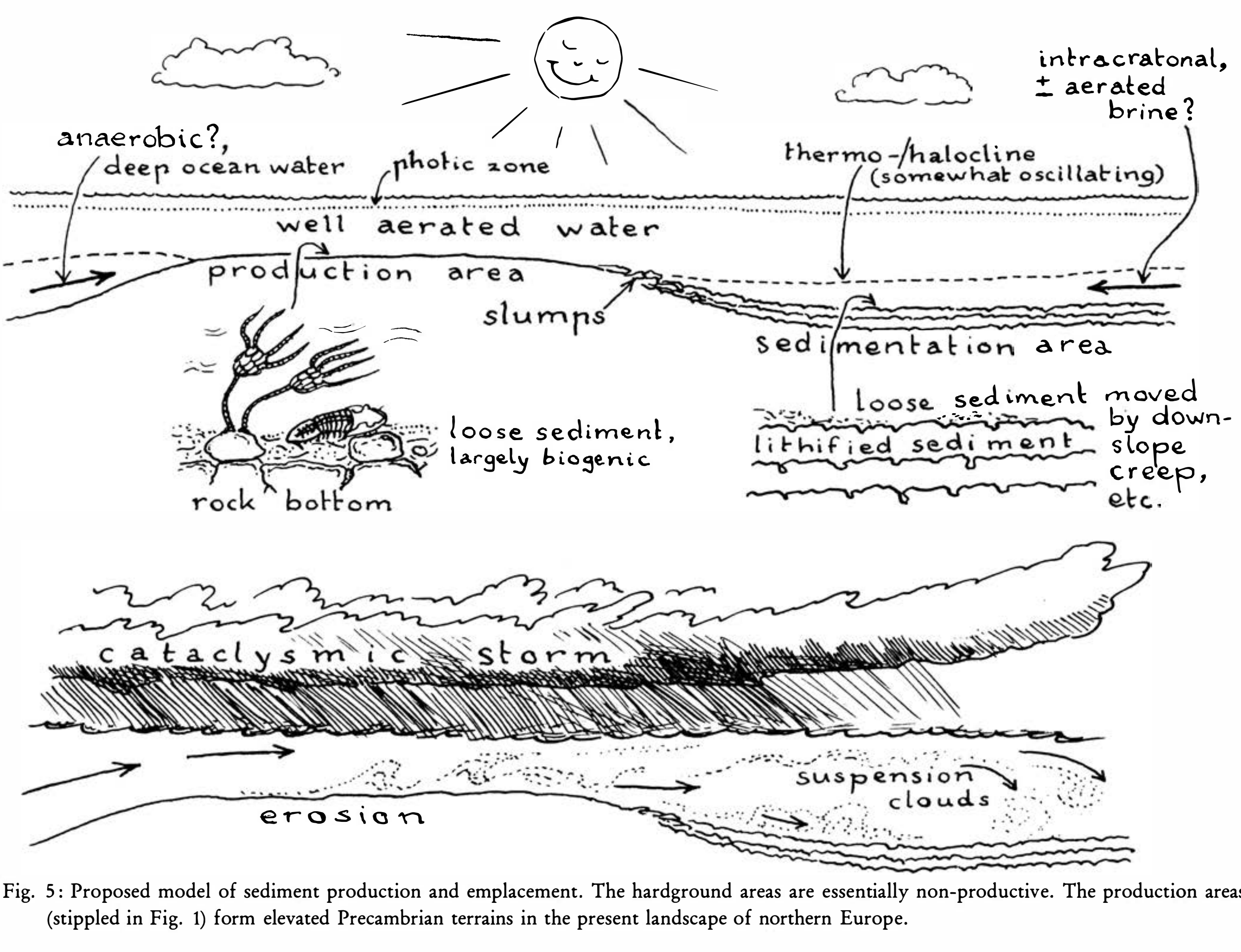

Fig. 5: Proposed model of sediment production and emplacement. The hardground areas are essentially non-productive. The production areas (stippled in Fig. 1) form elevated Precambrian terrains in the present landscape of northern Europe.

b) Turbidity currents. Unlikely, because they would have destroyed the fold structures (LINDSTRÖM 1963) that belong to the principal evidence for a quiet environment, and because directional structures are lacking.

c) Storm suspension (hypothesis of BOHLIN). Settling from storm suspension could produce grading and would not necessarily form directional structures. Shapes and sizes of the grains would permit suspension transport at velocities not greater than 1m/sec. The general absence of algal structures and skeletons of major benthonic animals suggests that the provenance areas were at depths of, say 100–200 m, rather than littoral or sublittoral. For the mechanism to function, storms must have been capable of generating the required current velocity at this depth and sustain it for some 30 hours, or the time necessary to transport particles about 100 km at about 1 m/sec. Since about half the suggested velocity normally occurs at different depths in current-swept parts of modern seas, it may be realistic to assume exceptional occurrence of sustained velocities even exceeding 1 m/sec at a depth of as much as 200 m. For comparison with a bioclastic limestone interpreted as a storm deposit, albeit at shallower depth, see BALL, 1971.

d) Creep down a gentle slope, combined with slumping. Slumping can be identified in several cases in which the beds were partly cemented before the event. The mechanism does not necessarily create oriented structures. It explains the chaotic inner structure of many beds. This feature led BOHLIN (1949) to formulate his deposition-by-storm hypothesis; however, it could perhaps equally well be explained by bioturbation and/or gas-driven percolation. Unlike the hypotheses a–c, the creep and slump hypothesis explains the presence of resedimented lumps of limestone floating within lime mudstone for instance in the Yxhult sample. The main difficulty with this hypothesis is that normally occurring inclinations of orthoceratite limestone beds are 1 m/100–1000 m and probably never were steeper than this. Because of this feeble slope, creep and slump movements are probably limited to special situations.

The tentative model of the orthoceratite limestone sea resulting from this discussion (Fig. 5) is a deep shelf with a bottom topography that resembles the Baltic Shield of today. Permanent deposition took place in the same major areas where Ordovician sediments still occur. The water depth was a few hundred metres. Higher terrain formed shoals that were the principal sites of biologic sediment production. The sediment of the shoals was subjected to decomposition by microscopic borers. Probably, production and oxidation of iron sulphide occurred as well. Commonly, skeletal fragments were covered by fibrous calcite cement; destruction of the host fragments left isolated calcite crystals as sediment particles (»ant-eggs«).

The sediment resulting from these processes was swept into suspension by storms. Rare, particularly forceful storms were capable of carrying the suspension to wide areas of deeper water where it settled. Fine mud, including AES, was to some extent separated from skeletal material. In areas close to the shoals, in particular where the latter were bounded by fault scarps (Yxhult and Borghamn), creep and slumping contributed to the transportation of sediment into the deeper areas.

The ecologic and physicochemical differences between the shoals and deeper water possibly require restricted vertical circulation in the water body. In Fig. 5 this is symbolized by a conjectural halo-/thermocline.

Summary and conclusions

During the Early Ordovician, extensive areas of the northern European continent were covered by so-called orthoceratite limestone, a starved facies with pelagic features. This facies contains a great number of hardgrounds. A few characteristic hardgrounds of Arenigian age are dealt with in this paper. Special attention is given to carbonate cementation, glauconite, the relation between pyrite, goethite and hematite, hardground morphology, and ecological conditions.

1) There is at least one hardground every 5 to 10 cm of the Arenigian orthoceratite limestone.
2) Each hardground may represent 25 000–125 000 years of interrupted sedimentation.
3) Investigated hardgrounds have yielded no body fossils of autochthonous, sessile benthos. Borings (and burrows?) indicate a sparse and specialized fauna. In the case of one hardground complex, known as »Blommiga Bladet«, it is suggested that the borers themselves kept the hardground in morphologic equilibrium by trapping (and consuming?) sediment.
4) Existing evidence indicates that the major portion of the calcareous sediment between the hardgrounds is allochthonous; it probably formed in areas shallower than the ultimate depositional areas. It may have been transported by processes of short duration, such as catastrophic storms.
5) The allochthonous material includes abundant particles referred to as »ant-eggs«. Each particle consists of a single calcite crystal. Most »ant-eggs« are 5–10 μm thick and 10–30 μm long. A lithology consisting mainly of »ant-eggs« is referred to as »ant-egg spar«, or AES; it is a variety of microspar.
6) »Ant-eggs« apparently formed as palisade-like syntaxial overgrowths, mainly on trilobite fragments. They were liberated through destruction of host particles. According to this interpretation they are an early generation of cement. Early formation of palisade-like overgrowths and »ant-eggs« is indicated by their inclusion in glauconite matrix.
7) Glauconite cements the surface of many hardgrounds. These glauconite occurrences indicate scarcity of animal activity on the sea-bed while the glauconite was forming.
8) Only calcite has been identified as carbonate cement. Magnesian and ferroan calcite have not been met with. Blocky calcite cement has been found intergrown with glauconite in such a manner as to indicate early crystallization of the calcite.
9) Radial aggregates of calcite cement, evidently grown in soft, permeable carbonate mud under the limestone crust of a hardground, have goethite and pyrite included in the calcite crystals. Pyrite inclusions are to some extent younger than the goethite. This shows that the goethite did not form through late oxidation of pyrite, and that calcite and pyrite growth were to some extent contemporaneous. Sea-water is likely to have provided sulphate for reduction to sulphide ions, hence the environment probably was marine. The calcite shows no evidence of recrystallization. It is regarded as primary early cement.
10) Further evidence that early cementation has protected goethite from dehydration to hematite – a process that would otherwise have occurred in the presence of water – is provided by many hardgrounds, the most significant instance being the one described from Hällekis.
11) Hematite and goethite pigment apparently formed by oxidation of iron sulphide or bisulphide.
12) Laminated stromatolite-like structures formed by rhythmic precipitation of sulphide, later on oxidized to goethite. Shrinkage cracks developed as the goethite was dehydrated to hematite. These cracks, filled by calcite cement, enhance the laminar structure. The »Blodläget« complex of hardgrounds offers good instances of the kind of structure.

13) Baryte cement replacing calcite has been found in particular at spots where there is evidence of oxidation of iron sulphide or bisulphide. The baryte contains goethite pigment.
14) Cementation of most hardgrounds appears to have proceeded from below upwards. At a certain stage the non-cemented sediment at the surface could be removed, leaving the lobose cementation front as a hardground.
15) Cementation by calcite was furthered by the alkalinity gradient within the sediment.
16) It may also have been furthered by sea-water with relatively low magnesium ion concentration.

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Plate 1

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Fig. 1, 2: Horns Udde, about 0.6 m above base of Ordovician. Glauconitic limestone with hardground. On the lower surface of the hardground crust there are radial calcite aggregates, strongly pigmented by goethite. Thickness of whole bed: 5 cm.

Fig. 3: Yxhult, about 0.3 m above base of Ordovician. Glauconite cemented hardgrounds. The dark zone surrounding the lower part of the pouch-like boring is finely disseminated pyrite. Width of upper, narrow part of the boring: 16 mm.

Fig. 4: Horns Udde, »Blommiga Bladet«. Horizontal section of anastomosing tubes connecting the vertical pits. Vertical pits have round cross sections. One of them (central right portion of picture) lacks goethitic aureole. Width of figured surface: 11 cm.

Fig. 5: Horns Udde, »Blommiga Bladet«. Hardground with cross sections of vertical pits. The overlying bed contained anastomosing tubes some of which cut into the hardground. Width of figured surface: 17 cm.

Fig. 6: Degerhamn, »Blommiga Bladet«. The sac-like pits have glauconitic crusts. Several borings are surrounded by pyrite aggregates reflecting yellowish white. Total thickness of the figured beds: 18.5 cm.

Fig. 7: Borghamn, »Blommiga Bladet«. Slumping took place between phases of hardground formation. Width of figured section: 12 cm.

Fig. 8: Shoreline north of Horns Udde, »Blodläget«. Goethite rich hardground removed from the major portion of the surface, whereby hematitic, stromatolite-like structures of the underlying layer are exposed. Width of figured surface: 25 cm.

Fig. 9: Shoreline north of Horns Udde. »Blodläget«. Goethitic hardground broken through in places, whereby hematite capped structures (largely orthocone cephalopods) of underlying layer are exposed. Width of figured surface: 35 cm.

Fig. 10: Horns Udde, »Blommiga Bladet«. Total thickness of the figured beds: 13.5 cm.

Fig. 11: Hällekis. Basal hardground complex of the orthoceratite limestone. See also Pl. 2, Fig. 8, 9. Thickness of figured bed: 8 cm.

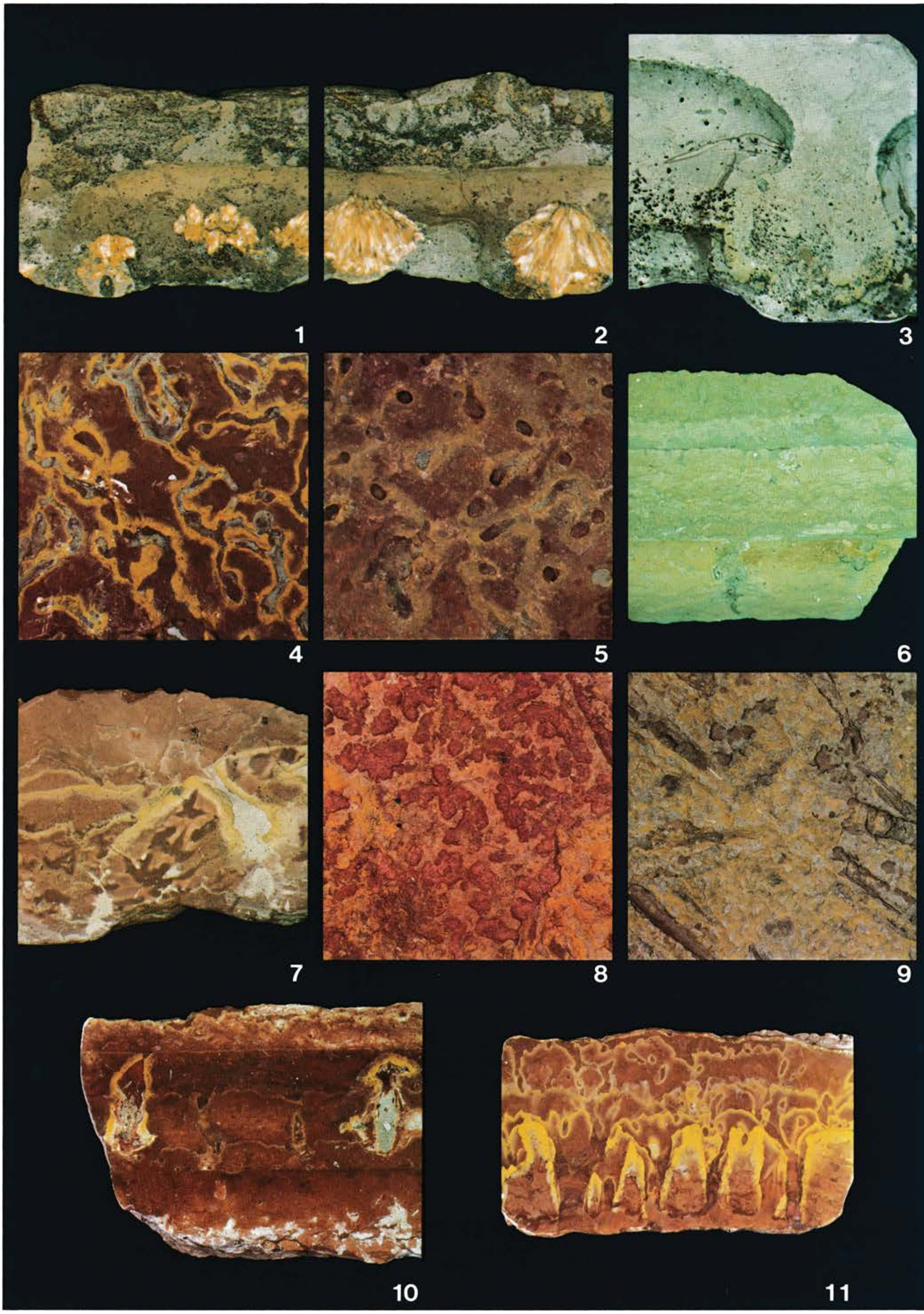
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Plate 2

Fig. 1: Araldite mould of carbonate particles included in glauconite, lowermost Ordovician, Yxhult (for preparation procedure, see text-fig. 3). SEM. Trilobite fragments with radial cement overgrowth and several isolated »ant-eggs«. Scale bar = 100 μm.

Fig. 2: Same sample and preparation as Fig. 1. Scale bar = 20 μm.

Fig. 3: Yxhult, same sample as Fig. 1. Plane polarized light. Microspar with portion of glauconite crust (dark grey). Embedded in the glauconite is, inter alia, a skeletal fragment with overgrowth of radial calcite cement. Scale bar = 200 μm.

Fig. 4: Yxhult, same sample as Fig. 1. Plane polarized light. Microspar (AES) with portion of glauconite crust that contains numerous »ant-eggs». Scale bar = 200 μm.

Fig. 5: Yxhult, same stratigraphic level as Fig. 1; sample Yx 1b. Angular calcite fragments enclosed by glauconite. Scale bar = 200 μm.

Fig. 6: Horns Udde, sample Hun 8, 1.4 m below »Blommiga Bladet«. Plane polarized light. Fracture filled by calcite spar and (coeval to younger) glauconite. The fracture ends at a glauconitized hardground. Scale bar = 500 μm.

Fig. 7: Detail of Fig. 6; scale bar = 200 μm.

Fig. 8: Hällekis, basal hardground complex of orthoceratite limestone. Plane polarized light. Junction of 1st and 2nd hardground from below. Left, fine grained AES underlying vertical 1st hardground. Right, horizontal 2nd hardground above coarser grained AES and overlain by microspar with less »ant-eggs«. Both hardgrounds goethite cemented below a thin crust with pure calcite cement. Scale bar = 200 μm.

Fig. 9: General view of structure shown in Fig. 8. Plane polarized light. The lithology cut by the 1st hardground is rendered dark by abundant goethite. The lithology cut by the 2nd hardground fills a fracture in the 1st hardground; it is red (hematite) in the deepest zone shown, then there is a bleached zone followed by a zone with goethite matrix. The youngest lithology shown (right margin of photo) has red hematite pigment. Scale bar 1 mm.

Fig. 10: Bjällum, east quarry. Lobate hardground from a limestone bed locally occurring within the Lower *Didymograptus* Shale. Stereopair. The hardground has a thin glauconite crust. Length of specimen: 30 cm.

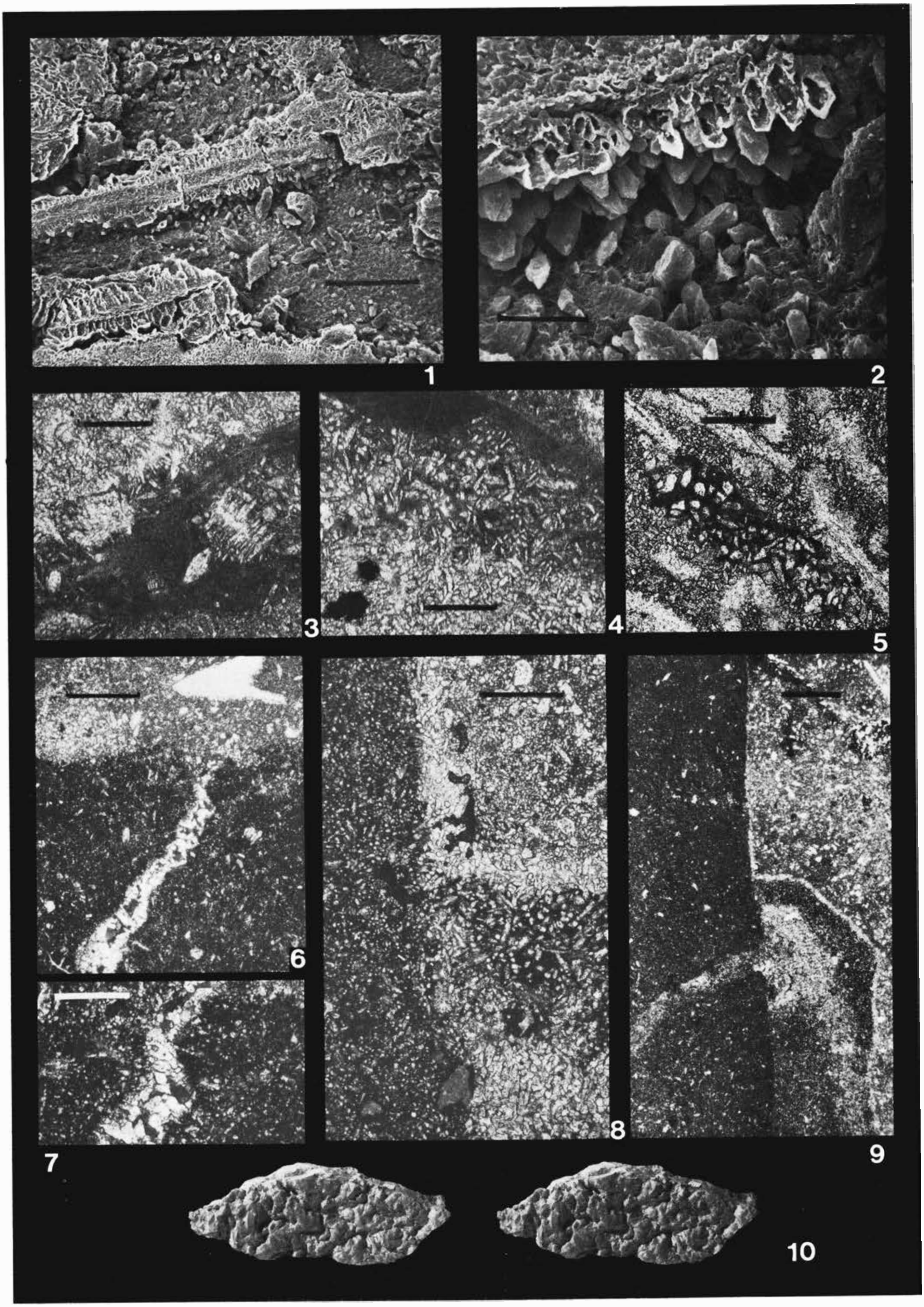
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Plate 3

Fig. 1: Shoreline between Horns Udde and Byrum. »Blodläget«. Polished section. Laminated, stromatolite-like caps of hematite above protrusions of lower hardground. Dark portions are red. Scale bar = 1 cm.

Fig. 2: Same locality as Fig. 1 and Pl. 1, Fig. 8, 9. »Blodläget«. Crossed Nicols. Hardground with baryte overlain by bioclastic packstone. The baryte (monocrystalline, black; in extinction position) replaces calcitic microspar and forms cement (?) round trilobite fragments. Several of the latter are darkened by goethitic pigment. Scale bar = 200 μm.

Fig. 3: Hällekis, basal hardground complex of orthoceratite limestone. Crossed Nicols. 3rd and 4th hardgrounds from below, with goethite pigment, the upper hardground overgrown with hematite cemented bodies; dehydration of goethite to hematite, accompanied by shrinkage, opened a crack along the surface. The crack is filled with radial calcite. The hematite wart to the left has baryte (in extinction position) at the core. Scale bar = 500 μm.

Fig. 4: Same sample as Fig. 3. Plane polarized light. Junction between 2nd and 3rd hardground from below; note AES under hardground 2. Scale bar = 200 μm.

Fig. 5: Horns Udde, about 0.6 m above base of Ordovician, same sample as Pl. 1, Fig. 1, 2. Plane polarized. Radial calcite aggregate; fringe of calcite crystal with growth trajectories marked by glauconitic (grey, mainly upper portion) and goethitic (dark) inclusions. Scale bar = 200 μm.

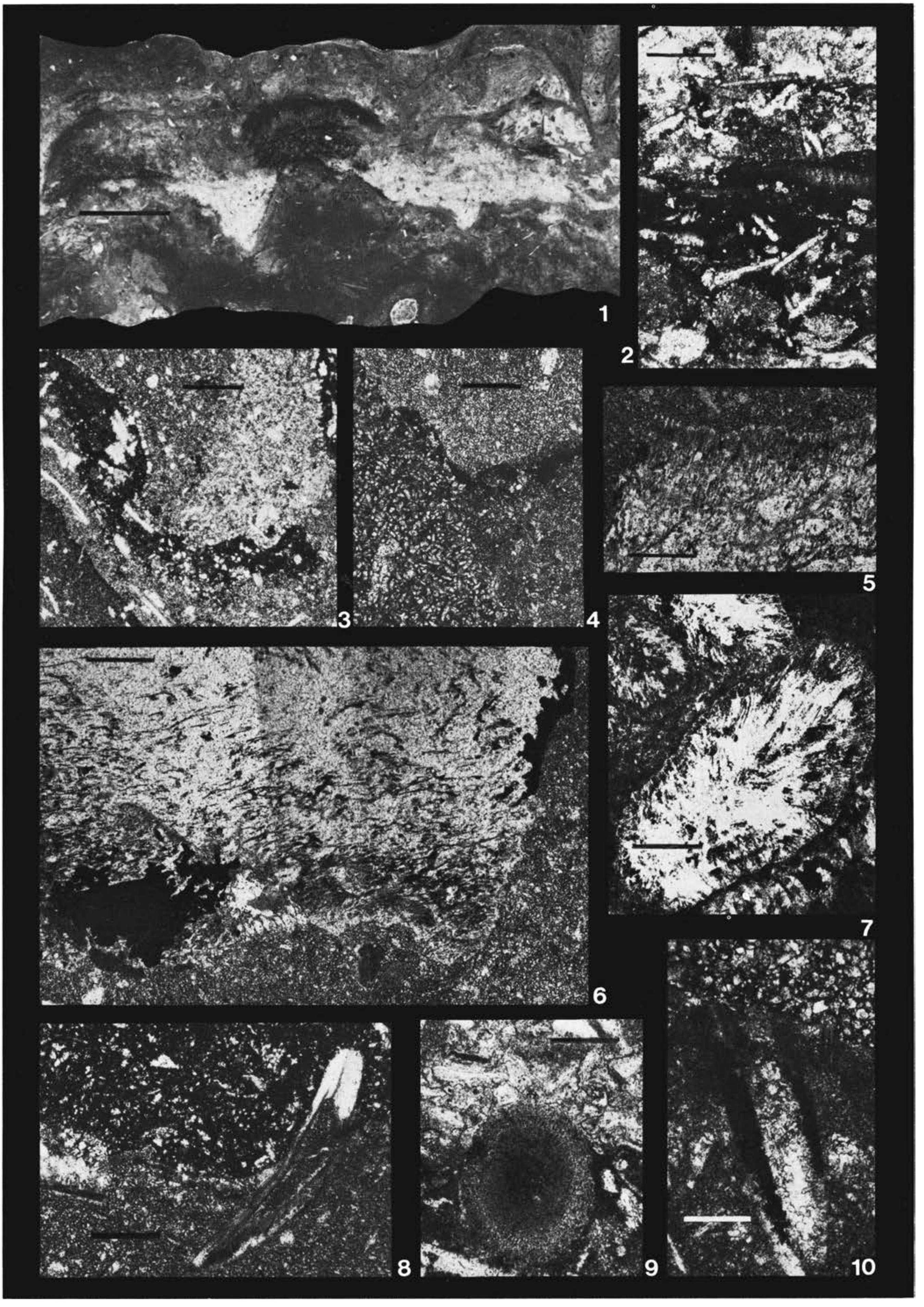
Fig. 6: Same sample and aggregate as Fig. 5. Plane polarized light. Calcite crystal intergrown with pyrite (upper right, lower left), glauconite (dark grey tones), and goethite (thin, dark streaks). Scale bar = 200 μm.

Fig. 7: Same sample and aggregate as Fig. 5. Crossed Nicols, showing lack of undulose extinction and subcrystals in obliquely cut calcite crystal. Streaks of goethite show growth trajectories. Scale bar = 200 μm.

Fig. 8: Horns Udde, »Blommiga Bladet«. Plane polarized light. Wall of pit, with goethite impregnation (dark grey) affecting part of a trilobite fragment that is embedded in the wall but not part projecting from the wall (right half of figure); the pit is filled with calcareous mudstone rich in hematite (black; upper part of figure). Scale bar = 200 μm.

Fig. 9: Same locality as Fig. 1. »Blodläget«. Plane polarized light. Goethite impregnated microsparitic hardground (lower half) with echinoderm ossicle with goethite impregnation particularly strong at center; superposed (upper half) by bioclastic packstone. Scale bar = 200 μm.

Fig. 10: Horns Udde, »Blommiga Bladet«. Plane polarized light. Wall of hardground pit that is filled with strongly hematite pigmented calcareous mudstone (upper 1/4). The wall of the pit consists of microspar rich in skeletal particles. Close to the filling the microspar is glauconitized together with a cylindrical trilobite fragment. The rest of the microspar and much of the trilobite fragment are goethite pigmented. The trilobite fragment encloses a filling of sparry calcite cement. The cement is not pigmented by goethite and is cut by the pit. Scale bar = 200 μm.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