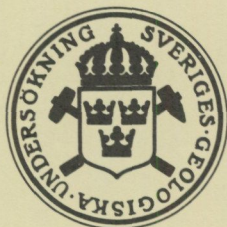


LESLEY CHERNS

THE HEMSE-EKE BOUNDARY
FACIES RELATIONSHIPS IN THE
LUDLOW SERIES OF GOTLAND
SWEDEN



UPPSALA 1983

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ABSTRACT

Cherns, L., 1983: The Hemse-Eke boundary: facies relationships in the Ludlow Series of Gotland, Sweden. Sveriges geologiska undersökning, Serie C, No. 800, pp. 1-45. Uppsala 1983.

Lithological sequences and faunal distributions across the Hemse Group-Eke Formation (Silurian, Ludlow Series) boundary along a strike transect on the Baltic island of Gotland, Sweden, indicate a general increase in water energy through this interval, representing overall shallowing in response to regional regression. The base of the Eke Formation is taken where macroscopic calcareous algae come into the sequence. Over a wide area in the east this level corresponds to a mineralized horizon, or zone of mineralization of sediments, and to marked lithological and faunal changes, but in the west there is a transition up into oncolitic facies. The biostratigraphical evidence suggests some diachronism of the primary mappable divisions comparable to that known for lower levels in the succession, with units younging to the east along strike. There is no significant stratigraphical break across the Hemse-Eke boundary. In the eastern upper Hemse sequences of argillaceous limestones and marls, early lithification and submarine cementation of carbonates, with local discontinuity surfaces and intraformational conglomerates, indicate slow net sedimentation leading to condensed sequences. Mineralized Hemse discontinuities commonly form the base level for episodic erosional downcutting through the overlying lower Eke carbonates, and this accentuates the facies changes at the boundary in the eastern region.

INTRODUCTION

The exposed Silurian sequence on the Baltic island of Gotland, Sweden, comprises a thickness of about 500 m of platform carbonates of late Llandovery to late Ludlow age. The virtually undisturbed strata dip very gently to the south-east (usually up to 2-3°), and there is extensive exposure across the strike, particularly in coastal sections. Major limestone developments in the succession include moderate to high water energy, inshore shelf deposits with reefs and carbonate mounds. To the south-west along the strike, these carbonate sequences pass laterally into more offshore, lower energy deposits of fine-grained, mostly fairly friable, muddy calcareous rocks generally referred to as "marlstones" or "marls". The lithofacies distribution reflects roughly sub-parallel depositional belts relating to a shore-line to the north (e.g. Jaanusson *et al.* 1979: fig. 4). The Gotland succession documents an overall, though pulsatory, regression through the Silurian which results in the progressive migration of the facies belts to the south-east; thus, the outcrop remains fairly consistently in shelf deposits, although subsurface data show a rapid transition southwards into offshore muds at all levels. A brief synthesis of depositional environments and palaeogeography for the Gotland Silurian is given by Laufeld & Bassett (1981).

The succession on Gotland has been divided into primary mappable units defined using a combination of lithological characteristics and diagnostic fossil evidence. Many of these major divisions include a wide variety of facies, and further subdivisions are mostly only of local application (see Laufeld 1974, for

summary of stratigraphy; modified terminology after Bassett *et al.* 1981, also Bassett *et al.*, in prep.). In the current study, sediments and faunas were examined in detail through the Hemse Group–Eke Formation boundary interval, where there is a marked facies change across the whole of the outcrop area. The aim of the work is to evaluate the facies and their palaeogeographical implications, as well as the biostratigraphical significance of this horizon.

STRATIGRAPHY OF HEMSE–EKE BOUNDARY SEQUENCES

The Hemse Group (Fig. 1), estimated by Hede (1921) from mapping to be c. 100 m thick, comprises a major, variable limestone development on the eastern side of the island, while to the west there are sequences of soft, muddy marlstones. The pronounced lithological and faunal differences between these two main areas are indicated by their distinction on the 1:50 000 geological maps. The limestone sequence is most complete in the north-east, Katthammarsvik region (used by Hede 1929, for subdivision of the Hemse Group), where the youngest beds locally are known as the Millklint Limestone (c. 6–7 m thick; Hede 1929:51). Since the outcrop of these beds is isolated geographically, their correlation with the upper Hemse Group strata in different facies in the main outcrop area further to the south is approximate. In the latter area, around Lau, the upper strata of the Hemse Group are argillaceous limestones and marls distinguished separately by Munthe (1910) as the “*Dayia* flags”. The overlying Eke Formation is a thin (max. 15 m; Hede 1921:66) division of marlstones, marly limestones and small carbonate mounds. The sediments are dominantly carbonates in the east but these pass westwards into marls in which the calcareous alga *Rothpletzella gotlandicum* is characteristic; the latter beds are “*Sphaerocodium* marl” of Munthe (1910).

For this study, sections across the Hemse–Eke boundary were measured at selected localities along a strike transect of the outcrop area (Figs. 1, 2). Thin sections and stained acetate peels were used to examine lithological samples, and limestone types were established by point counting, using the classification outlined by Jaanusson (in Jaanusson *et al.* 1979:20). Faunal records were made to accompany the sedimentary logs. Macrofossil records are based partly on field identifications, supplemented by selective collecting. Microfossils were extracted from sieved, washed marl samples and acid insoluble residues. Faunal data are mainly qualitative, although with some indication of the variation in relative abundance of the common macrofossil groups; quantitative results are based on point counting of the skeletal sand in thin section. Figured material is deposited with Sveriges geologiska undersökning, Uppsala (SGU Types 1420–1436 and R(ock) O(riginals) 70–82). Locality names follow the reference list in Laufeld (1974a), except for new localities which are described in the Appendix (p. 44). Localities are given 8-figure grid references according to the Swedish National

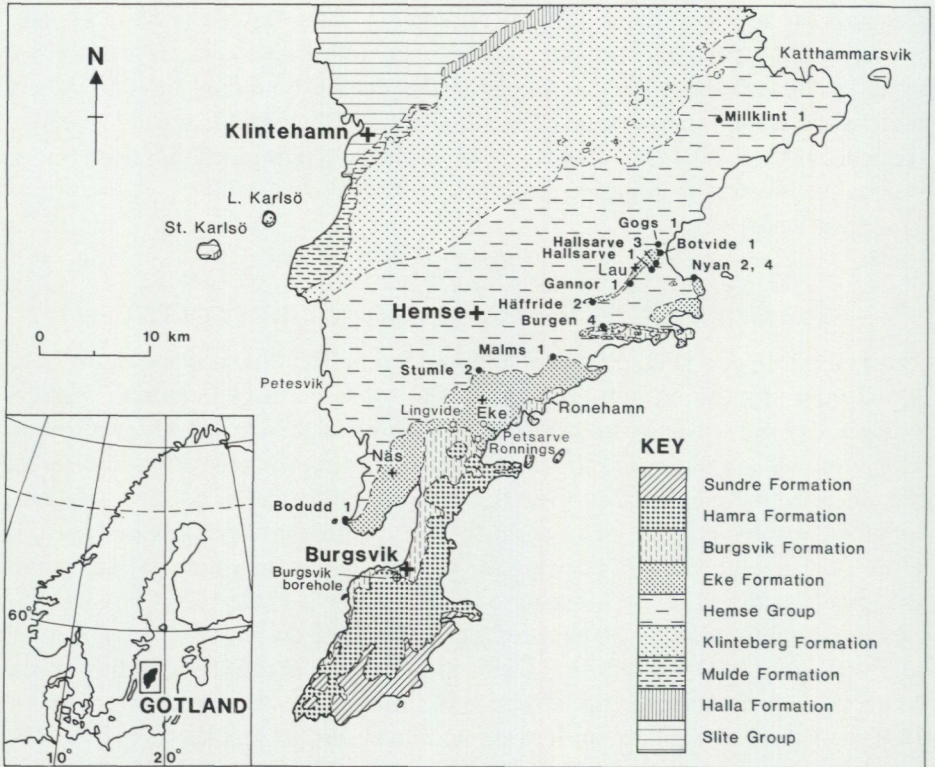


Fig. 1. Geological map of southern Gotland showing the positions of localities along the Hemse-Eke boundary transect detailed in Fig. 2 (black circles), and additional localities discussed in the text (open circles, and borehole \oplus).

Grid (Rikets nät) for the 1:50 000 topographical map sheets 6J Roma SO, 6J Roma SV, 5I Hoburgen NO and 5J Hemse NV; all lie within the 100 km grid square 63 16.

The detailed stratigraphy of sections can be grouped geographically into sequences from eastern outliers together with the eastern part of the main outcrop area, the western part of the main outcrop area, and the northern, Katthammarsvik area sections of Millklint 1. In each case the base of the Eke Formation is taken at the level where macroscopic calcareous algae come into the sequence. In the east this level corresponds to the lithological and faunal change taken to mark the boundary by Hede (1925:38) in description of the profile at Lau kanal (= Gannor 1 of Laufeld 1974a: Fig. 1 and see below), while in the western, marl sequences Hede (1921:66) considered *R. gotlandicum* as the key fossil for the Eke Formation.

EASTERN REGION

Localities studied: Nyan 2 (5367 7489), Nyan 4 (5375 7495), Gogs 1 (5634 7132), Botvide 1 (5578 7156), Hallsarve 3 (5442 7104), Hallsarve 1 (5418 7095), Gannor 1 (5284 6887), Häffride 2 (5090 6555), Burgen 4 (4858 6704), Malms 1 (4562 6236).

The Hemse–Eke transition on the east of the island is best exposed at localities around the Lau outlier of Eke Formation strata (Fig. 1), which forms a prominent topographical feature elongated along the strike. The section at Lau kanal (= Gannor 1) was used by both Hede (1925) and Munthe (1902) as a reference for the stratigraphy in this region. The Hemse–Eke boundary is also exposed in coastal outcrops further east, near Nyudden (Nyan 2 and 4). To the south and south-west of the Lau district, the Hemse–Eke transition crops out only in isolated, drainage ditch sections. Burgen 4 lies in a more southerly outlier of Eke through to Hamra Formation strata, and Malms 1 is further south, on the main outcrop area of the boundary level.

HEMSE GROUP

Lithology – The uppermost Hemse Group consists of fairly carbonate-rich sequences of marlstones interbedded with thin, argillaceous and silty limestones. The bedding is mostly thinly flaggy, with the harder, more calcareous lenses and bands becoming prominent on weathering. Calcareous nodules give an irregular appearance to the bedding at some horizons. The marl beds are commonly shaly to 1 or 2 cm thick, and some have a finely laminated fabric. Bioturbation affects all the upper Hemse Group sediments to various extents. In some beds discrete, narrow silt-filled traces (*Chondrites*) are directed parallel and oblique to the lamination, while in others there is a heterogeneous texture and diffuse mottling caused by dense accumulations of micritic particles which represent indurated pelletal grains, indicative of extensive biogenic reworking (cf. Fig. 3G). Among the laminated sediments, small-scale current structures are common and many units have thin basal calcareous lenses with concentrations of bioclastic material. Some more massive laminated units have gently undulating upper surfaces, reflecting low angle, internal ripple cross-bedding. A few bedding sole surfaces display aligned tool marks; most indicate currents flowing from north or north-west. At Häffride 2, near the south-western tip of the Lau outlier, bedding surfaces with shallow, symmetrical round-crested linear ripples are fairly common among loose but local debris. Two such beds in the boundary section (Fig. 2) show ripple crests striking E–W and SE–NW (N 82° W and N 135° W, respectively).

Many of the limestones are calcilutites with a low amount of skeletal sand and high terrigenous clay content. A micritic pelletal texture is common even in deposits where scattered skeletal grains are fairly numerous (e.g. Fig. 3B). There

SW

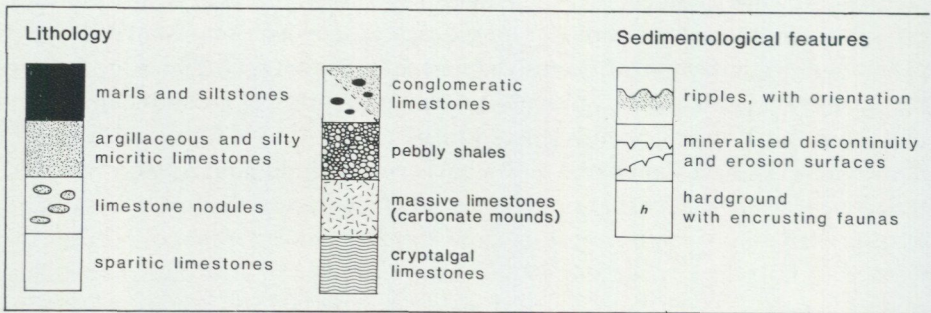
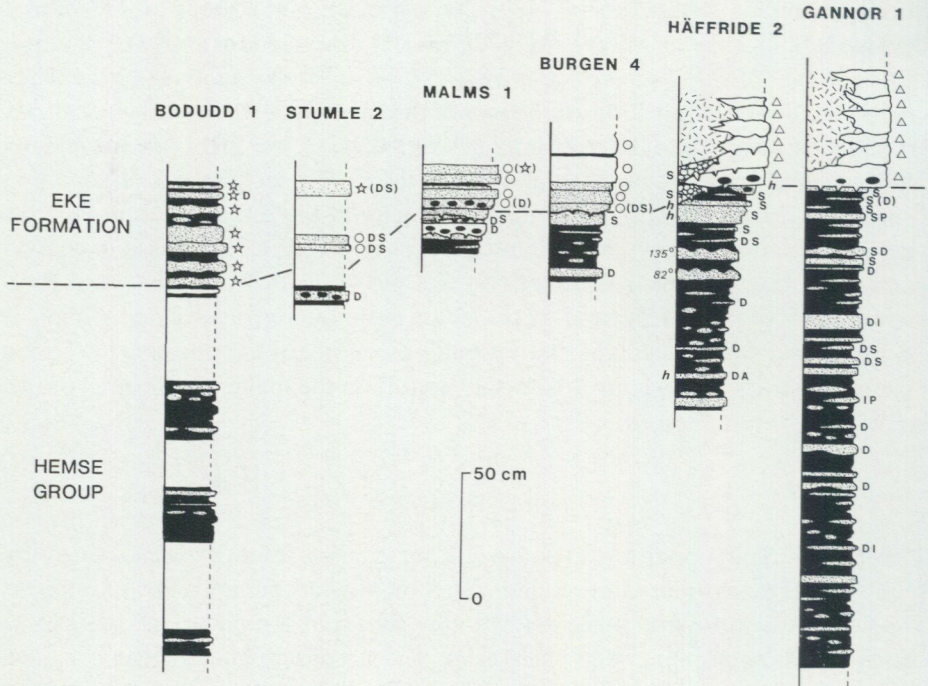
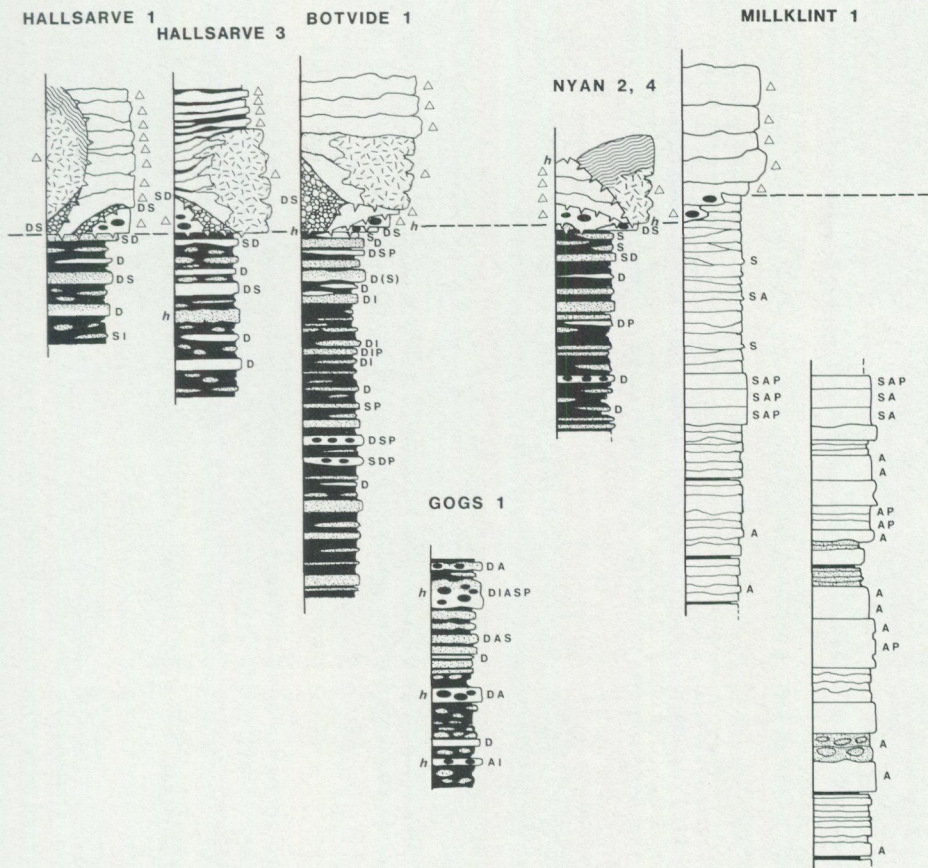






Fig. 2. Measured sections at key localities along the Hemse-Eke boundary transect (Fig. 1) from SW-NE, showing lithological sequences, sedimentological features, the nature of the algal component in Eke sediments, and the numerically prevalent species in prominent skeletal

NE



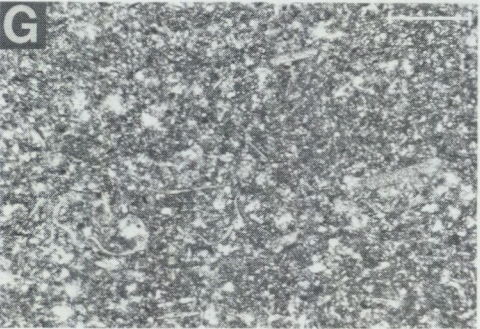
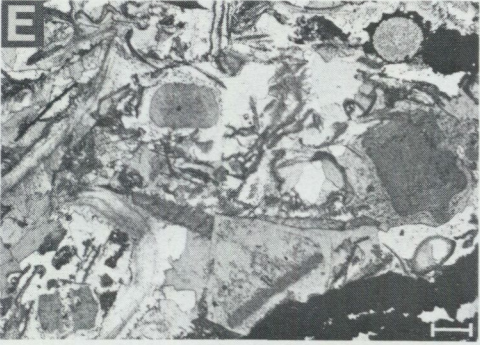
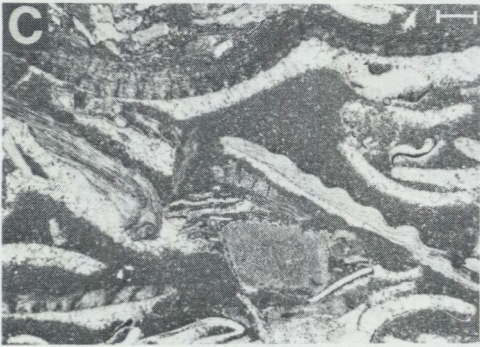
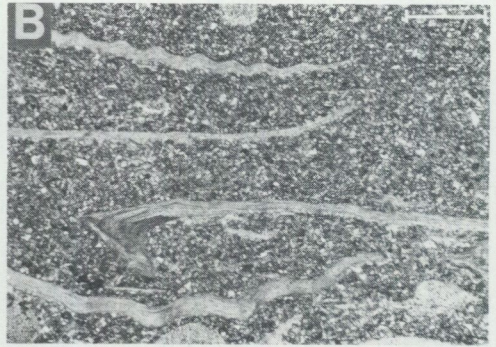
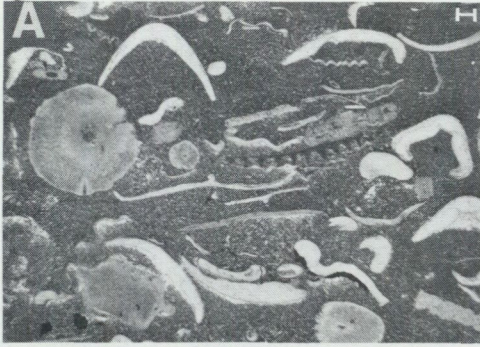
Algal component

-  stromatolites
-  fragmental and micritised algal debris
-  "smooth" oncolites
-  *Rothpletzella* oncolites

Brachiopods dominant

- A *Atrypa* spp.
- D *Dayia navicula*
- I *Isorthis canaliculata*
- P *Protochonetes striatellus*
- S shaleriids

concentrations dominated by articulate brachiopods. In each section, the base of the Eke Formation is taken where macroscopic calcareous algae come into the sequence.



are some extensive, bedding surface accumulations and lenses of skeletal material, and these become increasingly common in the uppermost part of the sequence. Skeletal fragments are mainly mud-supported in the micritic skeletal calcarenites (e.g. Figs. 3C, D). Grain-supported limestones are those fewer, thicker and denser skeletal concentrations which are also characterized by sparitic intergranular cements and void fillings (e.g. Fig. 3E, which also shows some micritisation of skeletal grains). In many skeletal calcarenites, winnowing of the finer material from the matrix is suggested by the micrite infills to intragranular cavities of skeletal particles. Winnowed or depositional cavities are indicated by thin geopetal spar linings beneath curved skeletal grains (e.g. Figs. 3C, D).

At Gannor 1, the uppermost c. 0.8 m of the Hemse Group comprises mainly marls and calcilutites in which skeletal material is largely limited to lenticular concentrations and thin calcarenite horizons. Apart from the levels with prominent skeletal layers (Fig. 2), many of the beds have only minor assemblages with restricted diversity faunas (p. 16). In thin section, some samples from these beds and from associated unfossiliferous calcilutites show dense concentrations of very small rhombs of dolomite as replacement of the micritic matrices, although skeletal grains are unaffected (e.g. Fig. 3F). Similar dolomitic intervals occur in the basal c. 0.5 m of the section at Botvide 1.

Early lithification – In marl beds of the eastern sequences (and typically in the western, marl sequences), much skeletal material is deformed by compression and aragonitic shells are preserved as moulds, showing that aragonite was dissolved before the sediment became lithified. In contrast, in some of the interbedded limestones, aragonitic skeletal particles are preserved as clearly

Fig. 3. Hemse Group limestone lithologies. Scale bar = 0.5 mm.

- A. Micritic calcarenite with low amount of sparitic rim and intergranular cements. Hallsarve 1; SGU RO 70.
- B. Calcilutite with matrix containing abundant small dark micritic grains, probably pelletal, and low amount of sparitic cement. Nyan 2; SGU RO 71.
- C. Micritic calcarenite with a high content of sparitic intergranular (geopetal) cement beneath skeletal grains, and many sparry calcite pseudomorphs after skeletal grains. Ditch exposure (5582 7023) on west side of road to Bolarve; SGU RO 72.
- D. Micritic calcarenite with sparry calcite pseudomorphs after aragonitic gastropod shells which retain original volume, and sparitic intergranular (geopetal) cement beneath skeletal grains. Gannor 1; SGU RO 73.
- E. Sparitic calcarenite with extensive sparitic cement including prominent rim overgrowths around echinoderm grains, and micritic envelopes around skeletal grains. X-nicols. Hallsarve 3; SGU RO 74.
- F. Calcilutite with dolomitization (small rhombs of dolomite) of the matrix although skeletal grains are unaffected. Gannor 1; SGU RO 75.
- G. Calcilutite with pelletal texture from abundant small micritic grains. The dispersed distribution of skeletal grains reflects intense bioturbation. Bodudd 1, SGU RO 76.
- H. Sparitic pelletiferous calcarenite with abundant micritic grains in the sparitic matrix. Skeletal grains are dominated by echinoderms (with sparry, rim overgrowths) and arthropods. Millklint 1; SGU RO 77.

delimited, drusy spar and microspar pseudomorphs which retain the original shell volume (e.g. Fig. 3D); this indicates lithification preceding dissolution of the aragonite and precipitation of calcite (e.g. Jaanusson in Jaanusson *et al.* 1979:20). A further indication of early lithification of carbonates is the only thin syntaxial rim cement around echinoderm grains in micritic calcarenites, the diagenetic overgrowth of calcite having been limited by the hardened embedding micrite matrix (e.g. Figs. 3A, C). Patchy lithification of many sediments is indicated by areas of local carbonate enrichment of the matrix and by the numerous nodular horizons.

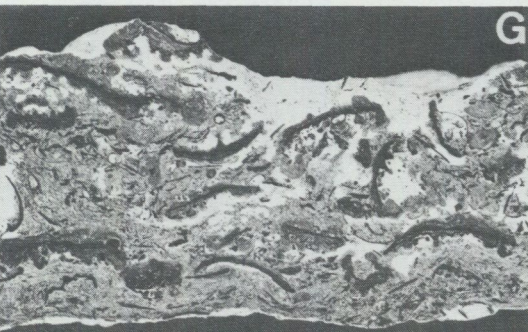
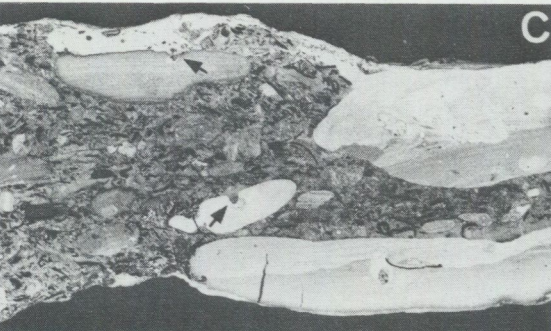
Within the top few metres of the Hemse Group, beds of fine-grained limestone which have irregular, lumpy upper and lower surfaces with marked relief become fairly common among the marls and nodular and argillaceous limestones. The boundaries of these layers are variably distinct from the sediments above and below, but generally the upper surface is more clearly defined. There is a gradation from laterally continuous, irregular limestone sheets to horizons of nodular sediments which locally comprise coherent carbonate layers. Lower in the sequence, nodular beds are less common and any associated layers of limestone are thin and impersistent. In the nodular limestones and across boundaries which are relatively diffuse, it is common that burrow traces continue from the limestones into the adjacent muddy sediments, showing that bioturbation was prior to lithification. However, for some of the irregular beds, *Chondrites* traces in the overlying marls terminate abruptly against the limestone relief (cf. Jones *et al.* 1979). These abutting burrows were evidently later than lithification of the carbonate, and indicate faunal reworking of soft sediment above the hardened layer while it was still not far beneath the surface. Other hummocky layers have deeply etched and scoured upper surfaces which are discordant to the bedding and truncate skeletal particles. In these beds erosion has been important, either in accentuating earlier uneven hardening or inhomogeneity of sediment type by removal of softer or less consolidated material, or by irregular dissolution and scouring of primary carbonates. Labyrinths of broad channels forming the raised areas of some surfaces may indicate preferential hardening of large burrow systems through the sediment (e.g. Fürsich 1973; Kennedy & Garrison 1975).

Intraformational conglomerates also become fairly common among the upper beds of the Hemse Group. The irregular limestones and the conglomerates appear closely associated; some of the former are themselves conglomeratic, pass laterally into or are overlain by conglomerates for which, by lithological comparison, they appear to have provided the majority of the intraclasts. Clast lithologies include argillaceous and skeletal limestones and calcareous siltstones. The clasts are well rounded, flattened and elongated parallel to their internal lamination, and the variously sharp contacts against the embedding matrix show that when reworked they had been lithified to differing extents. There are relatively few clasts where incomplete hardening is evident from plastic deforma-

tion associated with bioturbation of the conglomerates. Lithification before redeposition is indicated for many clasts by the clean truncation of internal lamination, bioturbation traces and skeletal fragments at clast margins, and by the failure of burrows in the surrounding matrix to penetrate the clasts (e.g. Fig. 4C). It is common that clast surfaces and internal burrow traces are micritic and mineralized (pyritized, phosphoritized), clasts are encrusted by epizoans (see p. 30, Fig. 4F) and there are small *Trypanites* borings into the rims (Fig. 4C). Both epizoan assemblages and borings are restricted to hard substrates (p. 30, 31). For several of the conglomerates, encrustation by epizoans across the upper surface of the bed indicates that these faunas became established post-depositionally. More commonly, only the intraclasts support epizoan faunas and most clasts are encrusted on all surfaces, so that epizoic attachment must predate deposition of the conglomerate.

Some of the irregular limestone layers have upper surfaces which are micritic, mineralized and encrusted by epizoans. In some beds, epizoans are restricted to the topographical "highs" of surfaces. The lower limits of the hummocky limestones tend to be transitional. However, there are rare beds in the uppermost Hemse Group which also have micritic and mineralized lower surfaces upon which encrusting biota are established (Nyan 4, Häffride 2; p. 31). The lack of any significant cutting out of adjacent strata suggests that these surfaces formed the roofs of narrow horizontal galleries, probably solution channels, in the near-surface lithified sediment.

Fauna – Fossils are only numerous in the uppermost part of the Hemse Group, concentrated in the many skeletal limestones. The fauna is dominantly of benthic invertebrates, particularly articulate brachiopods. The most common of these are *Dayia navicula*, a shaleriid (= *Strophomena impressa* Munthe 1902: figs. 3, 4, *nomen nudum*; see Bassett & Cocks 1974:17), *Isorthis canaliculata*, *Protochonetes striatellus* and *Atrypa* spp.. The inarticulate brachiopod *Craniops implicatus* also occurs widely. Among the microfossils, the large beyrichiacean ostracode *Neobeyrichia lauensis*, together with *N. scissa*, becomes very common in some skeletal calcarenite assemblages, including in dolomitic intervals. At Gannor-1, ostracodes form up to 14% of skeletal sand in dolomitic limestone samples, compared with a usual component of less than 5% in Hemse limestones. Tentaculitids are fairly common constituents of faunas; *Odessites inflatus* and *Dicricoconus tenuissimus* are the characteristic assemblage of these beds (Larsson 1979). Trilobites, which include *Calymene puellaris*, encrinurids and proetids, have a widespread distribution; although rarely prominent in skeletal assemblages they consistently compose 5–10% of the skeletal sand, occasionally up to 18%. Calymenids are notably common in dolomitic beds. Among bryozoans, the large bifoliate cryptostome *Ptilodictya lanceolata* is commonly conspicuous in assemblages, but bryozoans constitute a high amount of the skeletal sand in many



limestones (up to 50%). Echinoderms, mainly crinoids, also form a major part of the skeletal sand (15–25%) although they are inconspicuous among the macrofossil assemblages. A few individuals of lingulid brachiopods were noted perpendicular to the bedding and thus apparently *in situ*, but these are rather more common in the lower, less fossiliferous beds of the upper Hemse Group. Faunas at Häffride 2 have a marked abundance of echinoid plates belonging to *Neobothriocidaris* among the echinoderm grains, and some assemblages include small colonies of favositid and heliolitid corals and stromatoporoids, and solitary rugose corals, as well as numerous large valves of leperditiid ostracodes. Further east, leperditiids occur only, and in low abundance, at Hallsarve 1.

Within the uppermost part (c. 0.5 m) of the Hemse Group in the eastern area, there are striking concentrations of *D. navicula* (e.g. Hede 1925: fig. 12) and shaleriids (e.g. Munthe 1902: fig. 3). The shells compose coquinas of variable lateral extent up to several metres across and which change rapidly in thickness (maximum 15–20 cm but usually less than 10 cm). The bases of skeletal lenses are sharp and slightly erosional on the beds beneath (e.g. Fig. 4A), but the upper boundaries are transitional because of bioturbational mixing with the overlying sediments. It is not unusual to find virtually monospecific concentrations of each of the two brachiopods forming adjacent and laterally equivalent deposits (see

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- Fig. 4. A. Skeletal lens of micritic calcarenite cutting erosively into a finely laminated, dolomitic calculitite. The skeletal material, dominantly arthropod (trilobite and ostracode) and brachiopod (mainly chonetid) grains, shows upward-fining through the deposit. Hemse Group, Gannor 1; SGU RO 73, $\times 1$.
- B. *D. navicula* micritic calcarenite with an uneven, mineralized upper surface, which forms the topmost bed of the Hemse Group, overlain by a conglomeratic sparitic calcarenite of the basal Eke Formation. The rounded intraclasts of the upper bed include *D. navicula* and shaleriid limestones of characteristic Hemse lithologies (e.g. centre left), and abraded fossils and limestones of Eke aspect (e.g. bryozoan nodule at top of bed). Botvide 1; SGU Type 1420, $\times 1$.
- C. Intraformational conglomerate. Micritic calcarenite with rounded intraclasts of bioturbated calculitite and calcareous siltstone which are elongate parallel to their internal lamination. Small *Trypanites* borings into clasts (e.g. arrowed, centre and top), micritic rims (e.g. the latter bored clast), and the truncation against clasts of bioturbation traces at the top of the bed indicate that the clasts were lithified prior to redeposition. Hemse Group, temporary exposure (5538 7009) east of road north-west from Mattsarve; SGU Type 1421, $\times 1$.
- D, E. Tapering borings into a mineralized hardground surface at the top of the Hemse Group. The borings have pyritized walls, and cut sharply through skeletal grains in the sediment; the infill of marl and bioclastic debris includes much pyrite. Nyan 4; SGU RO 78, $\times 4$.
- F. Argillaceous limestone intraclast which has a micritic rim and is encrusted by an epizoic bryozoan, in a bed of micritic calcarenite. Hemse Group, ditch exposure (5582 7023) west of road to Bolarve; SGU RO 72, $\times 2$.
- G. Oncolitic skeletal calcarenite, mainly sparitic but with patches of micritic matrix. The majority of large skeletal grains (mainly brachiopod valves) have lobate *R. gotlandicum* coatings. Irregular mixing of marl down into the upper part of the bed results from bioturbation. Eke Formation, Bodudd 1; SGU Type 1422, $\times 1$.
- H. Oncolitic calculitite of bed underlying G, with disturbed fabric indicating intense bioturbation, and scattered, fragmented *R. gotlandicum* oncolites introduced by burrow mixing. Eke Formation, Bodudd 1; SGU Type 1423, $\times 1$.

also Munthe 1902:41); this is displayed well at Nyan 2 and 4. There is generally much bioclastic debris associated with the sparitic skeletal assemblages, and the majority of brachiopod shells are disarticulated, and commonly chipped or broken. Most coquinas dominated by *D. navicula* (e.g. Fig. 4B lower part) contain relatively few articulated shells. Many concentrations are notably depleted in the smaller, lighter brachial valves, while the more convex pedicle valves, which have a thickened umbonal region, commonly form dense accumulations. (However, in some assemblages a high proportion of the pedicle valves lie convex surface up and the brachial valves, even if present, are obscured, so that valve ratios and disarticulation cannot always be assessed.) In shaleriid coquinas, there is locally some imbrication of valves (e.g. Gannor 1, Nyan 2 and 4) but generally both concave-up and convex-up orientations are common and there is a wide range of individual size. The amount of breakage varies greatly laterally within assemblages.

In the dolomitic beds the relatively restricted faunas are composed of arthropods (mainly beyrichiacean ostracodes and calymenids) and *P. striatellus*. The latter also forms a major constituent of the skeletal sand in these beds.

Since the epizoan faunas of Hemse and Eke strata are similar in composition they are discussed together (p. 30). A few of the intraformational conglomerates include vertebrate fossils among the skeletal assemblages (e.g. Gross 1968; Janvier 1971, 1978). Similar vertebrate material was found in pockets of skeletal calcarenite filling in the scoured surficial cavities of an encrusted limestone from a temporary exposure near Lau (5397 7055), in what is evidently a winnowed, condensed deposit on the irregular surface. The vertebrate faunas in samples from the Lau area processed in this study include thelodonts and acanthodian scales (*i.a.* *Thelodus parvidens*, *Phlebolepis elegans*, *Lauaspis* sp., *Nostolepis striata*, *Gomphodus* spp.) and the teleostome *Andreolepis hedei*.

HEMSE-EKE BOUNDARY

The Hemse-Eke contact in the eastern region is widely marked by a planed or irregular, corroded and limonitized surface, which locally has a thin ferruginous crust with phosphorite, glauconite and pyrite (e.g. Gannor 1, Nyan 4, Burgen 4; also Spjeldnaes 1950). In lower beds, selective mineralization is confined mainly to pyritization affecting the rims and burrows in some intraclasts, burrows in some argillaceous calcilitites, and thin coatings on some skeletal grains.

At Gannor 1, there is no angular discordance at the top of the Hemse Group but the contact with the overlying massive Eke limestones is sharp. The uppermost bed of the lower division has a limonitized, eroded surface at which shells are truncated. Shallow cavities into the bed are lined by mineralized crusts, and filled by irregularities in the base of the overlying coarse limestone. Similar surfaces are developed at the top of the Hemse Group at Häffride 2 and Burgen 4. Since the

crusts cover surfaces which are clearly discordant in detail to the bedding, it is evident that the pockets are erosional features and not the result of loading by the overlying Eke beds into soft sediment. At Gannor 1, mineralized and micritic surfaces extend short distances laterally out from the cavities into the adjacent sediments; they follow the contacts between thin, upward-fining laminated units, and this shows that there was drainage solution through from the eroded surface. Shells exposed at the limonitized undersurface of one of these slightly lower beds support an epizoic assemblage similar to that of "galleries" at other localities (p. 31), although for shell substrates it cannot be excluded that the epizoans became attached prior to deposition of the bed.

At other localities, the top of the Hemse Group contains a zone 10–15 cm thick with several mineralized levels, narrowly spaced or merging laterally into a single, diffuse area of uneven corrosion and limonitization. At Botvide 1 and Hallsarve 1 this zone is clearly erosional and cuts out beds across the exposure. Coastal outcrops at Nyan 2 and 4 show considerable lateral variation in the boundary sequence. The topmost Hemse surface here is in some places planed smooth, in others is irregular and pitted with pyritized borings, and only locally preserves a mineralized coating. This surface is coincident in part with scalloped erosion surfaces in the lower Eke Formation (p. 19), and only in those areas has epizoic faunas and borings. Besides Nyan 4, encrusting faunas are established directly on the mineralized sediment of the topmost bed of the Hemse Group only at Botvide 1 and Häffride 2 (Fig. 2). At the latter, the top Hemse surface is markedly discordant through coquinas of shaleriids, where it truncates numerous valves. The surface is crossed by cracks, and rare examples have been found of epizoans – attachment discs of *Ptilodictya* and other encrusting bryozoans – moulded over the edges of cracks and thus evidently later than them (Fig. 6C).

Both at Botvide 1 and Malms 1, the most pronounced of several levels of mineralization is within the top part of the Hemse Group. At Malms 1, an irregular calcilutite layer at the base of a pebbly skeletal calcarenite has its limonitized surface covered by a prominent mineralized crust. Rounded intraclasts of calcilutite in the higher part of the bed have thick phosphatized and pyritized rims. The basal calcilutite is cut out in places to leave the conglomerate directly on the mineralized sediment of flags beneath. Unfortunately, the crusted surface is seen only in section in this limited outcrop. The next higher bed, a thin *D. navicula* limestone which has a limonitized upper surface, is partly cut out by an overlying thin lens of shaleriid-rich limestone that is eroded and limonitized. An unfossiliferous bed follows before sediments referable to the Eke Formation.

PEBBLY SHALE FACIES

(Fig. 2)

Shaly calcareous siltstones and marls which contain numerous abraded pebbles occur as impersistent intercalations and pockets among the topmost beds of the

Hemse Group, across the Hemse–Eke contact and among the carbonates of the lower Eke Formation. Many occurrences are associated with limonitized horizons, and the major distribution of this facies is related to erosion surfaces in the lower Eke Formation (p. 19).

The clasts are dominantly of Hemse lithologies and fauna. Many are heavily encrusted by epizoans and some also have borings; the generally very worn epizoan skeletons indicate prolonged reworking before deposition. At the top of the Hemse Group at Botvide 1, a *D. navicula* limestone with an encrusted upper surface passes laterally and vertically into limestone conglomerates and pebbly shales in which clasts of similar facies are encrusted across all faces (Fig. 4B). These clasts are mostly thin and platy, and they include some which are only 1–2 cm thick yet up to 25–30 cm across. Despite the abraded preservation they evidently are derived locally. In the similar pebbly deposits among the Eke limestones, the clast populations also include worn and broken colonial organisms and pieces of coarse calcarenitic limestones typical of the basal Eke strata.

The fine-grained embedding sediments include much fragmental debris; among this, the relatively robust shells of *Atrypa* and *Leptaena* are commonly conspicuous in deposits from Eke sequences.

EKE FORMATION

Lithology – The basal Eke Formation strata in the eastern region are dominated by massive skeletal sparitic calcarenites (e.g. Fig. 5A) and some calcirudites, and beds are commonly conglomeratic. As in the pebbly shale deposits at this level, the intraclasts in limestones include many of typical Hemse lithologies and fauna as well as others comprising abraded colonial organisms and limestones of Eke facies (e.g. Fig. 4B). “Water-worn” fossils in the basal limestones at Gannor 1 were noted by Munthe (1902:17) and Spjeldnaes (1950:216). Gravel grains (2–5 mm) are mostly worn and well rounded skeletal particles (dominantly crinoids, but also bryozoans, corals, brachiopods, and calcareous algae) together with some small lithoclasts. The limestones include well winnowed, grain-supported sediments with sparitic cements (intergranular and rim overgrowths: e.g. Fig. 5A). In other beds the skeletal material is at least in part mud-supported, and intergranular cements are variably micritic and sparitic (e.g. Figs. 5B, C). Many skeletal grains show neomorphic alteration to microspar. Micritic envelopes and peloids are commonly algal, and there are a few oncolitic coatings and nodules (Figs. 5A–D). As with some upper Hemse carbonates, preservation of the shell volume of originally aragonitic shells (e.g. arrowed in Fig. 5B), indicates early lithification. Eke limestones characteristically weather to a yellow-brown colour because of a high content of small goethite flakes (e.g. Spjeldnaes 1950).

Occurring irregularly among the coarse, bedded limestones there are lenticular biostromes and small (up to a few metres across) unstratified carbonate mounds

(the Eke reefs of previous literature). The mounds comprise heterogeneous, micritic and sparitic calcarenites, with intercalations and pockets of marl that give some idea of the original geometry as having had little elevation above the surrounding sediment. The flanks are marked sharply by massive, unstratified, sparitic crinoidal calcarenites which wedge out away from the mounds (e.g. Munthe 1902: fig. 5; Fig. 2).

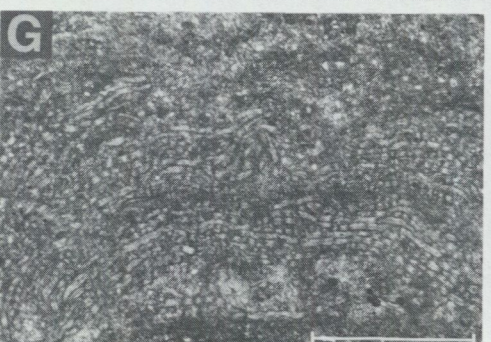
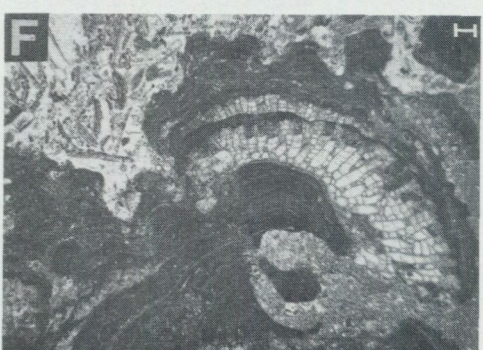
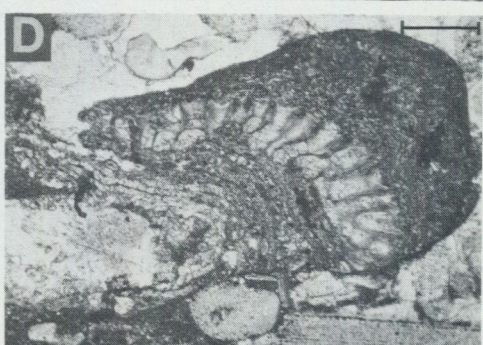
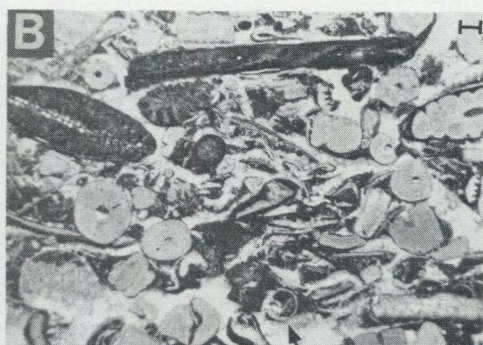
Higher strata and intermound sediments are dominantly more thinly bedded, nodular marly limestones and marlstones. The limestones comprise micritic to sparitic calcarenites, with variable skeletal sand content and fairly high amounts of terrigenous mud. These beds are extensively bioturbated, with a clotted pelletal texture in thin section. Particularly the upper boundaries of limestones are transitional because of burrow-mixing from the sediment above. In contrast, the grain-supported sediments of the mound flanks lack traces of burrows.

Over a limited area the lower Eke carbonates include closely spaced, extensive, scalloped erosion surfaces (described separately; Cherns 1982). The eroded beds show small solutional features in the surficial zone, aragonitic grains are leached, skeletal grains are truncated and there are some encrusting faunas and borings on the surfaces. These features show that the beds were lithified prior to erosion. The sedimentary cover of the discordant surfaces comprises carbonate sequences similar to the beds below, including some carbonate mounds directly upon the surfaces (e.g. Hallsarve 1, Nyan 4; Fig. 2) and pebbly shale deposits (p. 18). Locally the initial infill on the surfaces is covered by massive cryptalgal calcilitites that represent stromatolites (e.g. Fig. 2).

Westwards along the strike, carbonate mounds and biostromes become less common and are not seen in outcrop beyond the Burgen outlier. The Eke Formation comprises instead oncolitic facies, of two kinds which have largely separate distributions (Fig. 2). The first belt to the west of the mound tract has oncolites in which concentric, micritic cryptalgal coatings surround skeletal grains or, less commonly, intraclasts, and which typically have even layering and a smooth outline (e.g. Fig. 5E). Sequences further west (= "*Sphaerocodium* marl"), have beds of irregular, lobate *R. gotlandicum* oncolites (e.g. Figs. 5F-H, 4G, H).

At Burgen 4, the lowermost bed of the Eke Formation is a micritic skeletal calcarenite containing scattered "smooth" oncolites. In the top of this bed and in overlying, mainly micritic limestones, oncolites are more numerous and the majority of skeletal grains have algal coatings. Slightly higher in the sequence there are massive, geothitic sparitic calcarenites with algal coated grains and much fragmental algal debris (e.g. Fig. 5B).

At Malm 1 the first appearance of oncolites (i.e. the basal bed of the Eke Formation) is in skeletal calcarenites similar to those at Burgen 4, interbedded with finely laminated calcilitites incorporating thin basal skeletal lenses. The lowermost bed with "smooth" oncolites is conglomeratic, containing many flat,



rounded limonitized pebbles mainly of Hemse limestones; pebbles exposed at the top of this bed are encrusted by epizoans. Cryptalgal coatings on grains become increasingly common and are thicker in higher beds. Lobate *Rothpletzella* oncolites appear first in low abundance among the concentrations of "smooth" oncolites, but become numerous in the top beds exposed, which are siltier and sparitic (Fig. 2). Both at Burgen 4 and Malms 1, in the micritic limestones, sediment in intragranular chambers of the oncolitic "nuclei" is commonly clay-rich by comparison with the matrices of these beds, which shows that some winnowing has taken place. However, a wide size range of oncolites occur together, and their limited external abrasion contrasts with the well-worn grains of the strongly winnowed, sparitic beds (e.g. Fig. 5E cf. 5B).

Fauna and flora – In the Eke limestones of the carbonate mound tract there is a pronounced change from the faunas of the underlying Hemse strata; most notably with *D. navicula* and shalериids forming no more than minor constituents of assemblages. The shelly faunas of mound and intermound limestones differ markedly in faunal emphasis although there is little qualitative difference. In the mounds, macrofossils compose relatively little of the total volume (c. 10–20%) and there is no organic skeletal frame. Isolated colonial organisms apparently *in situ* are scattered in the massive limestones, but overturned and broken colonies are also common, especially towards the edges of the mounds. Mound and biostrome faunas are dominated quantitatively by colonies of low-domed and laminar stromatoporoids and tabulate corals (favositids, heliolitids and some syringoporids, with auloporids as common encrusters). Colonies are small in size

Fig. 5. Eke Formation limestone lithologies. Scale bar = 0.5 mm.

- A. Sparitic calcarenite dominated by echinoderm (crinoid) grains, commonly with rim overgrowths of sparry calcite. Micritic filamentous algal debris is common, e.g. two large patches in central area. Gannor 1; SGU RO 79.
- B. Variably micritic and sparitic calcarenite with micritic, algal coatings around a high proportion of skeletal grains (dominantly crinoids and bryozoans). Both grains and coatings are abraded and rounded. Sparry calcite pseudomorph after aragonitic gastropod shell (arrowed—lower centre) retains original convexity. Burgen 4; SGU RO 80.
- C. Micritic calcarenite with large brachiopod valve which has a lobate algal coating. Dark patches in the matrix are micritic algal debris. Nyan 4; SGU RO 81.
- D. Abraded oncolitic covering around nucleus of crinoidal limestone, in a sparitic calcarenite. The oncolite comprises the calcareous alga *R. gotlandicum* (patches of beaded filaments are clearly visible) intergrown with an encrusting cryptostome bryozoan (microspar-filled zooecia). Gannor 1; SGU RO 79.
- E. Micritic calcarenite with "smooth" oncolites. Concentric micritic coatings around skeletal grains (mostly trilobite) have a fine even layering (cf. 5D, F). Some limited abrasion of oncolites is evident at the narrow tips of elongated individuals. Malms 1; SGU RO 82.
- F. *R. gotlandicum* oncolite with lobate, irregular form to the concentrically layered, micritic covering. There are encrusting cryptostome bryozoans (spar-filled zooecia) intergrown among the algal fabric. Stumle 2; SGU Type 1424.
- G. Detail of F showing beaded filaments of *R. gotlandicum*.
- H. Detail of a *R. gotlandicum* oncolite showing *Wetheredella* intergrown among the micritic algal layers. Petsarve; SGU Type 1425.

by comparison with those of the major Högklint and Hamra reef developments (e.g. Riding 1981). Rugose corals are numerous in both mound and intermound facies; an example of the latter is the classic Lau backar 1 locality (5489 7985) where the solitary, operculate *Rhizophyllum gotlandicum* is locally abundant (e.g. Lindström 1882; Munthe 1902). Bryozoans are more conspicuous in mound limestones, where they include a wide variety of growth forms and *P. lanceolata* forms a distinctive member. However, bryozoans are a major component of the skeletal sand in both mound and intermound limestones (20–35%). Coenitids are locally abundant (e.g. Franzén 1982), although not in the sections examined in detail here. Echinoderms, predominantly crinoids, are particularly abundant in winnowed, skeletal sands and gravels flanking carbonate mounds, where they constitute up to c. 85% of the skeletal sand; this compares with an amount of 40–50% which is found in many limestones, both in and among the mounds. Articulate brachiopods are more widespread in intermound sediments, e.g. at Lau backar 1, where there is a notable abundance of individuals, including small size fractions. However, in the mounds there are some small, patchy concentrations of brachiopods, which include many articulated individuals. The common brachiopods of the Eke Formation include *Atrypa* spp., *Leptaena* spp., *Delthyris elevata*, *Microsphaeridiorhynchus nucula*, *I. canaliculata*, *P. striatellus* and *Homeospira baylei*. Trilobites are widely distributed but more common in intermound facies, the usual assemblage being *C. puellaris*, encrinurids and proetids including *Proetus (Lacunoporaspis) obconicus*.

Both at Burgen 4 and Malms 1 there is a more transitional faunal change through into the basal Eke strata, with *D. navicula* and shaleriids continuing to be common in the lowermost beds. At Burgen 4, there is a marked overall faunal change in the sparitic limestones at the top of the section, where the grain-supported deposits have assemblages dominated by colonial organisms, brachiopods and trilobites, and skeletal sand is mainly of echinoderm and bryozoan debris. In the lower oncolitic limestones, there is an increased abundance from the Hemse strata of proetid and calymenid trilobites, echinoderms, *P. lanceolata* and delthyrid brachiopods. At Malms 1, by the beds with *Rothpletzella* oncolites (Fig. 2), brachiopods have become quantitatively unimportant but bryozoans and solitary rugose corals are common. It is notable at both these localities that the decline in abundance of the common Hemse brachiopods takes place within oncolitic strata and higher than levels of erosion and mineralization of sediment.

WESTERN REGION

Localities studied: Stumle 2 (4375 5548), Bodudd 1 (2960 4460–2945 4470), Bodudd 2 (2941 4475), Petsarve 2 to 15 (3960 5633–3836 5764).

Further towards the west the sequences of both Hemse and Eke sediments are

less calcareous and are muddier. Outcrops are generally limited, and the best exposure of the boundary interval is at Bodudd 1, on the coast at the tip of the Näs peninsula. Inland, there is insufficient vertical thickness of strata in drainage ditch sections to allow logging of the sequences, but an isolated locality, Stumle 2, provides an important link between the sections at Malms 1 and Bodudd 1. The Eke Formation at Petsarve was examined briefly because there the *Rothpletzella* oncolitic facies is well developed; also, from not far away at Ronnings (Fig. 1; 3849 5570), Martinsson (1962:58) recorded the stratigraphically useful ostracode assemblage *N. lauensis*-*N. scissa*, which is characteristic of the upper Hemse Group further to the east (p. 27).

HEMSE-EKE TRANSITION

At Bodudd 1, a short sequence including the Hemse - Eke transition can be followed in offshore cuestas of very gently dipping strata on the northern side of the point (although only accessible at low water). To the south of the point, oncolitic strata crop out. There is a swing in strike of 15-20° in the beds near the point, evident from lateral discordance in the line of cuestas, but the zone of convergence of the differently trending strata is concealed by drift deposits. The similar lithology and fauna of beds either side of this area suggest that the discordance is due to a small N-S or NE-SW trending fault, and any displacement appears to be negligible.

Lithology - At Bodudd 1 the Hemse sediments are irregular nodular argillaceous calcilutites and marls in beds mostly 1-5 cm thick. The limestones generally have a low amount of skeletal sand and a high terrigenous content, and micritic matrices (Fig. 3G). Original bedding fabric is indistinguishable in many beds, where a disordered texture indicates intense bioturbation. In other beds, some patches of lamination remain although penetrated by diffuse burrow traces infilled with marl and fine skeletal debris. Skeletal material is otherwise concentrated into thin, debris-rich calcarenitic lenses which occur sporadically. There is a gradual transition in lithology corresponding to the incoming of oncolitic facies, with an increasing proportion of micritic and sparitic calcarenite beds among the muddy sediments (Fig. 2). Oncolites are mostly concentrated in the calcarenites, although some beds of calcilutite include scattered and fragmental oncolites which have apparently become introduced by burrowing activity (e.g. Fig. 4H). In the highest strata exposed, skeletal oncolitic calcarenites form the dominant lithology, and marly and silty partings are thin. The terrigenous clay content in these limestones is generally less than in the lower beds of the sequence.

Fauna and flora - Fossils are relatively sparse in the upper Hemse sediments. The more common components are the articulate brachiopods *Atrypa* sp., *I.*

canaliculata, *D. navicula* and *Morinorhynchus crispus*, *C. puellaris* and proetid trilobites, cyrtocone and orthocone nautiloids (commonly encrusted by epizoans), small gastropods and the bivalve *Goniophora* sp. One cluster of six aligned and articulated individuals of *Goniophora*, embedded with the commissural plane vertical, probably represents an *in situ* assemblage; this horizon is directly below the first appearance of algal coatings on skeletal grains. In beds slightly lower than the section in Fig. 2, Laufeld (1974b) reported a current aligned assemblage of orthocones.

From the initial development of thin algal coverings on some skeletal grains in the upper part of detrital accumulations, there is a rapid increase in their abundance and thickness up into beds with numerous oncolites. The algal encrustations are lobate and irregular, and the bands of beaded filaments preserved in some parts are typical of *R. gotlandicum* (e.g. Figs. 5F, G). At the level where the first algal coverings are present, rhynchonellid brachiopods and *Howellella elegans* become more common. Among the lower oncolitic strata one limestone has a dense concentration of *D. navicula*, and the species is also common in several other beds around this level (Fig. 2). In the oncolitic strata, there is gradual change in faunal emphasis through the sequence exposed. In the higher beds exposed at Bodudd 2, the common brachiopod fauna includes *Strophonella euglypha*, *Anastrophia ?deflexa*, *Leptaena* sp., *Atrypa* sp., *H. elegans*, *Dalejina hybrida* and *Whitfieldella* sp., but *D. navicula* is scarce. Solitary rugose corals, *P. lanceolata*, gastropods including *Loxonema* spp., orthocone nautiloids, and the bivalves *Cypricardinia* sp. and *Pteronitella* sp. are fairly common among assemblages. Echinoderm grains are a major component (25–40%) of the skeletal sand.

At Stumle 2 (Fig. 2), a conglomeratic skeletal limestone rich in *D. navicula* and trilobites occurs among poorly fossiliferous marls of the upper Hemse Group. Slightly higher there are micritic calcarenites rich in echinoderm grains, with "smooth" oncolites and common *D. navicula* and shaleriids. These beds are followed by similar limestones containing lobate *Rothpletzella* oncolites (e.g. Figs. 5F, G) and a fauna dominated by *P. lanceolata*, *I. canaliculata* and *Atrypa* sp., but with *D. navicula* and shaleriids still quite common. No evidence of a mineralized horizon was found in this very limited exposure.

The Eke Formation at Petsarve includes irregular skeletal calcarenites (1–6 cm thick) in which *Rothpletzella* oncolites are numerous. Winnowing of the skeletal accumulations is indicated by small pockets of marl in intragranular cavities and beneath curved shells. The intervening marls and siltstones are intensely bioturbated and many have a pelletal texture. The common brachiopod fauna is similar to that of the highest beds at Bodudd 2 but with the addition of *M. nucula*, *Ancillotoechia bidentata*, *P. striatellus*, *Coolinia* sp. and *Coelospira pusilla*. In the upper part of some oncolitic limestones there are low diversity clusters of brachiopod individuals without algal coverings which appear to be *in situ*

populations, most notably of *Atrypa* sp. Assemblages with and without algal coatings are broadly similar in composition. Generally the oncolites are little abraded, except for some beds where those exposed at the upper surface are worn and encrusted by epizoans (particularly serpulids).

NORTHERN, KATTHAMMARSVIK AREA

Locality studied: Millklint 1 (6784 7601)

HEMSE-EKE TRANSITION

Lithology – The highest beds of carbonate sequences are exposed in cliff sections at Millklint 1. Below the measured sections of Fig. 2, the sequence comprises thinly bedded, argillaceous and silty nodular limestones with many thin marl partings. These pass up into (bottom of Fig. 2) thin to fairly massive, tabular bioclastic limestones and irregular, nodular argillaceous limestones, with fewer, commonly laterally impersistent beds of marl. In thin section the limestones show dense concentrations of small indistinct micritic particles, which mostly represent indurated pelletal grains; these beds are sparitic pelletal calcisiltites and sparitic pelletiferous calcarenites (Fig. 3H). Irregular mixing of marl down into the upper part of limestones reflects biogenic reworking; by contrast, small pockets of marl which line concavities of shells in sparitic limestones represent remnants shielded during winnowing of the skeletal sands. Among the tabular limestones, much skeletal material is finely fragmented and whole shell layers are fairly few. The basal portion of some such beds is markedly coarser. A number of the skeletal calcarenites are lenticular and have erosional lower contacts. Higher in the sequence tabular limestones are thicker and more frequent, and some form low angle foresets in cross-bedded units up to 20 cm thick. Interbedded with these there are thick, lenticular, grain-supported skeletal deposits in which shells are imbricated, with many chipped or broken. Higher beds are again thinner and mainly finer grained (sparitic pelletal calcisiltites).

Near the top of the section there is a sharp lithological change in which massive, coarse sparitic calcarenites and calcirudites replace the finer grained limestones. The contact is undulating and locally cuts out beds, although across much of the outcrop it follows the bedding. There are biostromes among the grain-supported goethitic sediments of the topmost limestones. Weathering out of pockets and intercalations of marl leaves a rubbly appearance to the limestones. Massive crinoidal calcirudites have a local distribution. In thin section the limestones show a marked content of algal debris, in contrast to the carbonates of the lower part of the section (Fig. 2). On this criterion the coarser limestones at the top of the section should be considered as Eke Formation.

Fauna and flora – The rather sparse fauna of the lower beds is dominated by articulate brachiopods; the most common is *Atrypa* sp. (large globose individuals), with lesser amounts of *P. striatellus* and *H. elegans*. *C. implicatus* and encrinurids are minor components of assemblages, while the skeletal sand is dominated by echinoderms (40–50%) and bryozoans. Large single valves of the bivalve *Megalomus* sp. are present at a few horizons. Occasional assemblages contain many articulated individuals of *Atrypa* sp. The thick skeletal coquinas of higher beds consist largely of single valves of *Atrypa* sp. and shaleriids, and the topmost Hemse limestones include some virtually monospecific assemblages of imbricated valves of the latter (Fig. 2). Other more diverse assemblages at this level include *C. implicatus*, *H. elegans*, *D. navicula*, *P. striatellus*, *I. canaliculata*, *C. puellaris*, encrinurids, and proetids including *Warburgella (Tetinia) ludlowensis*. Vertebrate assemblages recovered from these beds were similar to those from Lau (p. 16).

In the coarse Eke limestones the fauna is different, dominated by colonial organisms (heliolitid and favositid corals, bryozoans and small stromatoporoids), solitary rugosans, *Atrypa* sp. and delthyrid brachiopods. Many of the colonial organisms are encrusted by epizoans, which are strongly abraded. Echinoderm debris is a major component of most limestones.

SUMMARY OF BIOSTRATIGRAPHY

In recognition of the basal Eke Formation sediments as containing an appreciable amount of calcareous algae, it is apparent that this facies reflects environmental control and traces conditions that can be expected to migrate geographically across the depositional gradient in the course of regressive/transgressive events. For lower stratigraphical units of the Gotland Silurian, diachronism in detail can be proved biostratigraphically from the evidence of combined macro- and microfossil distributional data (e.g. Bassett *et al.* 1981a). Thus, the base of the Hemse Group is demonstrably diachronous, its age ranging from *nilssoni-scanicus* Biozone on the west coast to *leintwardinensis* Biozone on the east (Bassett *et al.* 1981; Bassett *et al.*, in prep.). Higher in the succession, however, the faunal evidence is more limited, particularly for those divisions cropping out in the narrow, southern peninsula of the island where the width of strike is greatly reduced. The youngest diagnostic graptolite evidence is the *nilssoni-scanicus* level of a few Hemse Group localities on the west coast (e.g. Petesvik: Hede 1942; Fig. 1) and in the Burgsvik borehole (Fig. 1) in comparable facies (Rickards in Bassett *et al.*, in prep.). The higher units of the Gotland succession were deposited fairly rapidly; microfossil evidence from the Hamra and Sunde formations indicates a pre-Downton age for these strata.

Beyrichiacean ostracodes provide a diagnostic correlation for the Hemse–Eke

transition. The *N. lauensis*-*N. scissa* assemblage (Martinsson 1962, 1967) indicates an international correlation of high in the *leintwardinensis* Biozone, and this is supported by evidence from associated tentaculitids (Larsson 1979), conodonts (Jeppsson 1974) and trilobites. Along the transect studied, neobeyrichiids are not recorded from the Millklint Limestone but the *lauensis*-*scissa* fauna is characteristic of the upper Hemse strata of the eastern region. Further west than Malms 1, the assemblage was not found in Hemse sequences but it is known from the Eke Formation at Ronnings (Martinsson 1962; Fig. 1). The short-ranging *N. scissa* (Martinsson 1967) is recorded also from the Eke strata at nearby Lingvide (Fig. 1), and to the south is present in the upper Hemse Group of the Burgsvik borehole (Bassett *et al.*, in prep.) The tentaculitid and conodont distributions for the Hemse and Eke divisions are of more limited value in local correlation. The tentaculitid fauna (Larsson 1979) of the upper Hemse sequences of the eastern sections is the *O. inflatus*-*D. tenuissimus* assemblage; the former species also occurs in the Millklint Limestone, but does not continue into the Eke Formation. In the higher division tentaculitids are sparse, especially in the limestone sequences. In the Eke marls a different assemblage, *Odessites prolatus*-*Tentaculites obstipus*, is present. The conodont fauna of upper Hemse strata from the Lau area and at Millklint belongs to the *Polygnathoides siluricus* Zone (Jeppsson 1974). However, this assemblage has not been reported from western sequences of Hemse strata, and samples processed from there during the current study failed to yield diagnostic elements; similarly, Eke samples contained poor, non-diagnostic assemblages. From the Eke strata at Botvide 1, Jeppsson (1974) reported a younger, *Hindeodella excavata* assemblage through at least the lower 5 m of the unit. The trilobite *C. puellaris*, which occurs widely in both upper Hemse and Eke sequences, provides useful indication that depositional breaks were insignificant in biostratigraphical terms, in relation to its limited range in Britain, being most common in the higher part of the *leintwardinensis* Biozone (Dr. D.J. Siveter, University of Hull, pers. comm. 1979). The proetid *W. ludlowensis*, which occurs in the upper Hemse limestones of Millklint 1, also has a restricted range in Britain within the *leintwardinensis* Biozone (Dr. R.M. Owens, National Museum of Wales, Cardiff, pers. comm. 1982); this confirms correlation of the Millklint 1 sections with the upper Hemse sequences further south.

The common brachiopods of the Hemse and Eke divisions are long-ranging species, so that compositional changes in assemblages appear to be of facies rather than time significance (i.e. faunal shifts *sensu* Jaanusson 1976). The relation of the acme of shaleriids in the upper Hemse Group to that of *Shaleria* (*Protoshaleria*) *ornatella* in beds of equivalent age in the British Ludlow cannot be assessed before the systematic position of the Gotland material is established (e.g. Bassett & Cocks 1974). The distribution of *D. navicula* does not provide an index horizon either; in Britain this species occurs in great abundance through intervals at various levels in the Ludlow (e.g. Whittard 1961: 69-70), and acmes appear to be

of relatively local significance. Particularly in the Eke carbonate sequences where faunas are dominated by colonial organisms, the faunal composition is evidently controlled by facies, and shifts reflect environmental changes.

PALAEOECOLOGY AND DEPOSITIONAL ENVIRONMENTS

The benthic invertebrate fauna can be divided for ecological consideration into groups utilising hard and soft substrates, and those with epifaunal and endofaunal life habits. In addition there are vagile organisms, which are taken separately since many do not fit readily into a single category (e.g. Jaanusson in Jaanusson *et al.* 1979). The fossil fauna comprises only a limited part of the benthic community, i.e. those organisms with preservable hard parts. In modern examples, Craig & Jones (1966) noted that the proportion of soft-bodied animals varies between about 40 and 70%, the higher figure relating to soft-bottom assemblages dominated by endofauna. There is a general inverse relationship between endofauna and epifauna, with the former increasing in importance in soft, fine-grained sediments and more offshore environments.

The activity of soft-bottom endofauna is evident throughout both Hemse and Eke sequences from bioturbation traces in the sediments. Particularly in the marls, the obliteration of much primary bedding fabric indicates intense reworking, and many flags have pelletal textures. The pelletal limestones of the Millklint 1 sections provide further record of soft-bottom organisms. However, the skeletal fauna includes few representatives of this ecological group, with none more than a minor component of assemblages. The inarticulate lingulid brachiopods were sessile infauna, and semi-infaunal life habits have been suggested for tentaculitids (Larsson 1979) and for bivalves such as *Goniophora*, *Pteronitella* and *Cypricardinia* (Stanley 1972).

Epifaunal, sessile articulate brachiopods dominate numerically in most skeletal assemblages of the upper Hemse Group. Among the prevalent species, *D. navicula*, shaleriids, *P. striatellus* and *Atrypa* spp. rested free on sediment in the adult stage after loss of the pedicle during ontogeny. Thus, early ontogenetic stages required a hard substrate for attachment, although commonly only a local area such as another shell or skeletal debris (Craig & Jones 1966; Worsley & Broadhurst 1975), but the brachiopods later became able to maintain stability unattached, on soft substrates. Jaanusson (Jaanusson *et al.* 1979: 269) termed such organisms "ambitopic".

At this level and through a limited stratigraphical interval, *D. navicula* and shaleriids occur intermittently in great abundance in assemblages over a wide area. Rich accumulations of skeletal material need not reflect a high standing crop if net deposition rate were slow (i.e. "time-averaging"), and the overall sedimentation rate in the Silurian of Gotland was only a few mm per thousand

years (e.g. Jaanusson in Jaanusson *et al.* 1979: 284). Further, net deposition rate was apparently minimal for the eastern sequences of the upper Hemse Group, characterized by depositional breaks and reworking of sediment and where the two brachiopods have their maximum abundance. Yet the wide size range of shells in many of the brachiopod assemblages dominated by individual taxa shows that these deposits are not rigorously current sorted, although winnowed and transported (p. 16). This suggests derivation from populations where large numbers and wide extent represent original distributional features. It appears that these species are "opportunistic" (MacArthur 1960), i.e. populations are capable of rapid temporary expansion in size. The distributions of the individual species differ in detail; shaleriids occur in abundance in the carbonate Hemse sequences of Millklint 1 where *D. navicula* is not common, whereas the latter is prevalent in the western marl sequences in assemblages of both Hemse and Eke strata (e.g. Fig. 2). There are marked fluctuations in species abundance through the sequences. However, factors affecting population dynamics among Recent marine benthos are complex, and temporal changes in population size over a period of years vary considerably within and among species even where no physical changes are observed (e.g. Blegvad 1928; Parker 1975). For species with planktic larval stages, recruitment of benthic populations even in a stable bottom environment is dependent not only on the initial abundance of larvae from spawning but also upon pelagic factors affecting the larvae, such as currents, fluctuations in food supply of phytoplankton, predation, and the duration of the larval phase (e.g. Thorson 1950). Physical changes in bottom conditions may provide observable explanation for differing composition of the established benthos, but it cannot be ruled out that intangible causes such as the levels of food resources may at the same time have been controlling factors.

The brachiopod rich assemblages of the upper Hemse Group also include some dominated by hard-bottom forms, such as the pedically attached *I. canaliculata*. However, in many skeletal accumulations both hard- and soft-bottom brachiopods are common (e.g. Fig. 2). Mixing of faunas by transport can explain this, but it is evident that the large populations of recumbent shells would have provided numerous, and commonly extensive, areas of hard sites for attachment.

The facies change at the base of the Eke Formation is accompanied by a marked qualitative shift in the brachiopod fauna. This is less pronounced in the west, although the appearance of algal facies is followed shortly by changes in composition of the brachiopod faunas (p. 24). In oncolitic beds there is a mixture of large reclining ambitopic forms, e.g. *S. euglypha*, *Atrypa* sp., and *Leptaena* sp., together with ribbed, pedunculate hard-bottom forms, e.g. *A. deflexa*, *H. elegans* and *C. pusilla*. At Petsarve (p. 24) there are apparently *in situ* populations of brachiopods among similar assemblages of algally coated individuals and grains. This suggests that brachiopod assemblages and oncolites are derived locally and thus that oncolitic environments were suitable for both soft- and hard-bottom

epifaunas. In the intermound facies of the Eke Formation carbonates further to the east, the brachiopod fauna also commonly includes both soft and hard bottom assemblages. The wide size range including small specimens in populations of various common species at Lau backar 1 (p. 22) suggests fairly local derivation for the assemblages. By contrast to the intermound sequences, in the grain-supported carbonates associated with carbonate mounds and biostromes brachiopods are only a minor component of faunas. The small pockets largely of brachiopod individuals which occur within mounds (p. 22) are dominated by single species, mostly pedunculate hard-bottom forms, e.g. *M. nucula*, *H. baylei*.

Of the mound faunas, many of the colonial tabulate corals and stromatoporoids were ambitopic, dependent initially upon a hard substrate for attachment (e.g. skeletal fragment) but then able to grow out freely over a soft substrate. This is an important factor in the development and the construction of the reef-like mounds in the Gotland succession since, unlike most modern reefs, they could establish in muddy sediment (Hadding 1941, 1950; Riding 1981). The Eke mounds lack organic frame and relief above the surrounding sea floor (p. 19, 21; also Jaanusson in Jaanusson *et al.* 1979: 24), and exerted little effect upon sedimentation in intermound areas. The colonial organisms appear individually to have occupied level bottom niches, based on local hard sites on carbonate sand (or less commonly gravel) or mud. However, the associated fauna in the mounds includes few soft-bottom representatives.

Hard-bottom encrusting and cementing, suspension feeding epifaunas preserved *in situ* indicate lithified substrates exposed on the seafloor, i.e. hardgrounds. Such surfaces include beds of the upper Hemse Group, pebbles from intraformational conglomerates and in the pebbly shale facies, colonial organisms in and around the carbonate mounds and biostromes, oncolites, and in the marl sequences large solitary skeletal fragments which formed local patches of hard substrate on otherwise soft mud bottoms (e.g. orthocone nautiloids at Bodudd 1). The commonly diverse and dense assemblages (e.g. Fig. 6) are quantitatively dominated by bryozoans, including a wide variety of encrusting growth forms, and also erect types like *P. lanceolata* which attach by a cemented basal disc (e.g. Franzén 1977; Figs. 6A–D). Other common members of the assemblages are tabulate auloporid corals (e.g. Figs. 6F, H) and occasionally syringoporids, the enigmatic organisms *Allonema* and *Condranema*, solitary rugose corals (Fig. 6G) and serpulid annelids (Figs. 6I, J). The latter include some individuals of *Anticalyptraea calyptrata* Schrenk (Larsson in Jaanusson *et al.* 1979: 103), which is particularly common from hardgrounds at Gogs 1 (Fig. 2). At that locality, one hardground assemblage has rare examples of craniacean brachiopods apparently attached directly to the surface sediment.

Attachment discs of bryozoans have a widespread and common distribution, but crinoid holdfasts (Fig. 6E) are much more numerous among the epizoan assemblages of Eke strata than in Hemse hardground faunas. In the Eke

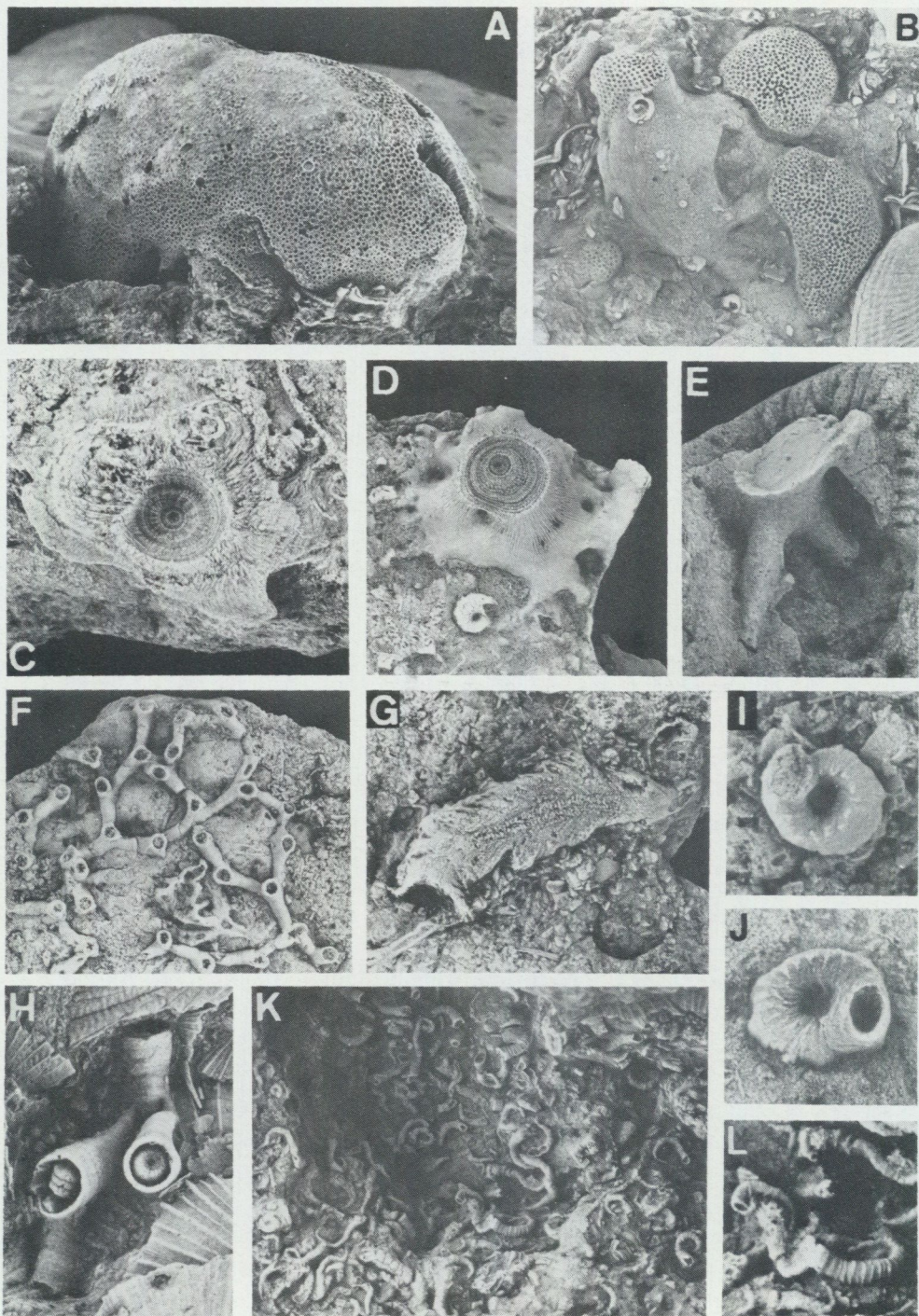
carbonate sequences, rooting structures of crinoids are common on colonial organisms but relatively few occur among the beds composed largely of crinoidal debris which form flank facies to the carbonate mounds. Crinoids are able to utilize a variety of substrates for anchorage although dependent on a hard object for larval attachment (e.g. Franzén 1977). The close association of crinoidal sands and gravels with the mounds and biostromes indicates that the detrital accumulations are derived from post-mortem dissociation of the plated skeletons and separation from the holdfasts and hard substrate.

It is notable that, apart from the limestones composed dominantly of crinoid grains, echinoderms rarely appear common among skeletal assemblages although they (crinoids and echinoid spines) widely form a major component of the skeletal sand of both Hemse and Eke limestones. This is partly a preservational effect correlated with the breakdown of echinoderm skeletons into numerous small and individually inconspicuous elements during fossilisation.

Small "cornulitids" occur in low numbers on many encrusted surfaces but their main distribution is on encrusted undersurfaces, as "gallery" faunas (e.g. Figs. 6K, L), where they occur in great abundance and high concentration, e.g. Nyan 4, Häffride 2. On many colonial organisms epizoans cover both upper and lower surfaces, which shows that at least some of the encrustation was post-mortem, even on apparently *in situ* colonies in the mounds; no examples of potential "shade" faunas (e.g. Spjeldnaes 1975) were identified from the mounds.

A further widespread occurrence of encrusting cryptostome bryozoans is as intergrowths among the fabric of calcareous algal structures, in both types of oncolite and also in stromatolites (e.g. Figs. 4D, F; Cherns 1982: fig. 5). This demonstrates that lithification of laminae accompanied the formation of the algal bodies. *Rothpletzella* oncolites fairly commonly also have intergrowths of *Wetheredella* (? foraminifer: Riding in Jaanusson *et al.* 1979; Fig. 5H). Some zoaria of encrusting bryozoans occur loose in limestones; this suggests that hard attachment surfaces also included non-preserved, firm organic substrates, e.g. non-calcareous algae (e.g. Brood in Jaanusson *et al.* 1979).

Hard-bottom endofauna are comparatively uncommon, especially by comparison with Mesozoic and Recent benthic communities (e.g. Bromley 1978; Kennedy & Klinger 1972). Borings affect areas of solution-eroded surfaces of the lower Eke carbonates, including parts coincident with the mineralized top Hemse bed (Figs. 5D, E; pp. 17, 19). They are also present on clasts in the pebbly shale facies and intraformational limestone conglomerates (e.g. Figs. 5C-E). Many of the borings are shallow pits referable to *Trypanites*, and the organisms responsible remain unknown. In the carbonate mounds and biostromes, borings are common on skeletal hard grains such as tabulate corals and stromatoporoids. At Nyan 4, on the upper surfaces of stromatolitic domes (e.g. Fig. 2), there are clusters of small borings. At this same locality, Richards & Dyson-Cobb (1976) reported *Lingula* occupying a number of bored cavities in colonial organisms.



Of the vagile benthos, scavengers or carnivores and deposit feeders included jawed polychaete worms, represented by scolecodonts, and some trilobites. These groups probably contributed to the reworking of surface sediment in the course of feeding, and some also by excavation of shallow burrows (e.g. calymenids, cf. Osgood 1970). Scolecodonts are common only in the oncolitic marl facies of the Eke Formation, but trilobite faunas of calymenids, encrinurids and proetids occur widely in skeletal assemblages of both stratigraphical divisions. Beyrichiacean ostracodes become numerically important in the upper Hemse Group of the eastern region (*N. lauensis*–*N. scissa* assemblage: Martinsson 1962), where some thin calcarenite lenses contain winnowed accumulations of disarticulated carapaces (e.g. Gannor 1). It has been suggested that increases in the abundance and diversity of palaeocope ostracodes relate to increased density of algal vegetation (e.g. Jaanusson in Jaanusson *et al.* 1979; Martinsson 1962). However, in the upper Hemse Group calcareous algae are not represented and the role of non-calcareous algae cannot be assessed. Gastropods, of which most were probably epifaunal browsers, are common only in the Eke oncolitic facies. Molluscs are in general poorly represented except in the latter sequences; partly this may be preservational, due to pre-lithification dissolution of aragonitic shells in marls and because recrystallized specimens in the early lithified limestones of

Fig. 6. Hardground faunas, Hemse Group.

- A. Encrusting trepostome bryozoan, *Hennigopora* aff. *claviformis*, on the upper surface of a hardground bed, Hallsarve 3; SGU Type 1426, $\times 1.5$.
- B. Encrusting trepostome bryozoans, *H.* aff. *claviformis*, and coiled serpulid worm (spirorbid) tubes, attached to topographical "highs" of a hardground surface, Häffride 2; SGU Type 1427, $\times 1.5$.
- C. Basal attachment disc of the cryptostome bryozoan *Ptilodictya* sp., cemented directly onto a mineralized, eroded surface and with part of its margin curled and grown over the sharp edge of a desiccation crack in the surface (lower part of picture). On the upper part of the disc there is the worn remnant of an encrusting serpulid worm tube. Häffride 2; SGU Type 1428, $\times 4$.
- D. Basal cemented disc of *Ptilodictya* and cemented serpulid worm (spirorbid) tube on the irregular upper surface of a limestone, Häffride 2; SGU Type 1429, $\times 2$.
- E. Discoid crinoid holdfast with irregular digitate margins, attached to the uneven, hummocky surface of a limestone bed, temporary exposure east of Lau (5397 7055); SGU Type 1430, $\times 4$.
- F. Tabulate aulopodid coral encrusting a limonitized limestone. In the calices of some corallites small peripheral septal spines are visible. Hallsarve 1; SGU Type 1431, $\times 2$.
- G. Solitary rugose coral (with worn encrusting bryozoan attached) anchored by rootlets and buttressing outgrowths (talons) onto a hardground, Botvide 1; SGU Type 1432, $\times 3$.
- H. Tabulate aulopodid coral with trumpet-shaped corallites and more erect form than F, septal ridges very weak and widely spaced or lacking. Häffride 2; SGU Type 1433, $\times 3$.
- I, J. Coiled serpulid worm (spirorbid) tubes cemented onto limestones.
I – Gannor 1, SGU Type 1434, $\times 5$.
J – Häffride 2, SGU Type 1435, $\times 5$.
- K. Small, curved and loosely coiled, encrusting conoidal shells ("cornulitids") attached among bryozoans and on the mineralized undersurface of a limestone bed, Häffride 2; SGU Type 1436, $\times 3$.
- L. Detail of K. showing annulate distal shell in larger (?adult) individuals, and the loose coiling or strong curvature of the apical end of shells on the substrate. $\times 7$.

the carbonate sequences are mostly unidentifiable. Other epifauna include the echinoids *Neobothriocidaris* and *Aptilechinus*, which were probably epifaunal browsers (e.g. Franzén in Jaanusson *et al.* 1979), and machaeridians; all occur widely in washed marl samples, although in fairly minor quantities.

The only evidence for floral abundance relates to the distribution of macroscopic calcareous algae, and these are restricted to Eke strata. In the west this is a matter of definition in sequences of transitional faunal and lithological changes, but in the east the widespread unconformity at the top of the Hemse Group is followed by beds containing calcareous algae (Fig. 2). In general, algae may be expected to become more important with decreasing water depth because of their dependence upon light for growth. For calcareous algae, the calcium carbonate saturation is also a limiting factor. However, the depth range of such algae is considerable; for example, Recent calcareous algae are known from depths down to c. 90 m although they are much more common at shallower depths (Riding 1975).

Relative levels of water energy can be inferred from sedimentological evidence although no direct extrapolation can be made from these to factors such as water depth, distance from shore or source area, depositional slope and current velocities; relationships are complex and affected also by local variables, e.g. sea floor topography of the carbonate mound tract.

The calcilutites, marls and siltstones of the upper Hemse Group, dominantly carbonate and terrigenous mud sediments, were laid down in generally low to moderate energy environments below wave base in offshore shelf areas. Interbedding of some finely laminated beds among more extensively bioturbated and pelletal sediments reflects fluctuating rates of deposition, since the amount of biogenic reworking relates more to time available than to the density of burrowing organisms (Howard 1975). Periodic strong current disturbances are indicated by skeletal calcarenites which are slightly erosive on beds beneath. Restriction of bioturbation traces to the upper parts of these layers suggests relatively rapid deposition. Generally the skeletal material is mud-supported, although a few grain-supported deposits indicate conditions of higher water energy. Faunas of these sequences are dominated by hard and soft bottom assemblages of sessile epifauna.

In the west, the sequences of well-bioturbated, fine-grained muddy sediments include fewer shell coquinas and have poorer skeletal faunas than sequences further east. The facies transition up into oncolitic beds at Bodudd 1 reflects a progressive environmental change. The accompanying lithological changes to carbonate rich, less muddy sediments indicate more current influenced deposition. Formation of oncolites requires agitated conditions in the photic zone, and generally takes place in very shallow, subtidal environments (e.g. Gebelein 1976). In the Eke sequences, *Rothpletzella* oncolites are mainly concentrated in the skeletal calcarenites which represent periods of higher water energy; interbeds of

bioturbated pelletal marls reflect intervals of quiet water deposition. Superficial epizoic encrustation and abrasion of oncolites are largely restricted to the upper part of oncolitic skeletal layers (e.g. Petsarve; p. 24), which indicates post-depositional exposure of current accumulations on the sea floor. The general increase in water energy through the Hemse–Eke transition suggests shallowing of the offshore shelf environment, with deposition of the oncolitic facies in inshore shoals within wave base. However, the transitional nature of the facies change makes it unlikely that the absence of macroscopic calcareous algae from the Hemse sediments relates solely to depth (p. 34).

Only in the northern, Katthammarsvik area, are the upper Hemse sequences dominated by carbonate deposition. Pelletal bioclastic limestones represent winnowed lime sands laid down during conditions of higher water energy than for the interbedded pelletal carbonate and terrigenous muds. The abundant micritic particles representing indurated pelletal grains indicate that hardening took place rapidly on the sea floor; such precipitation is widespread in the Recent lime sands of the Bimini Lagoon and Bahamas, in warm shallow conditions (= "bahamites" of Beales 1958). The sediments suggest that deposition was in shallow conditions, where water energy fluctuated but with generally relatively sheltered environments. In higher beds the thick, winnowed shell coquinas and cross-bedded carbonate sands result from intermittent periods of high current energy. Unfortunately the outcrops are insufficient to allow current directions to be ascertained or to show the geometry of the sediment bars and related shell lag accumulations. The much lower proportion of muddy sediments among these beds reflects an overall increase in water energy, and Eke strata at the top of the section show continuation of this trend. The well winnowed coarse skeletal sands and gravels, locally with biostromes including abraded, reworked fossils, indicate conditions of high current energy. The marked content of algal debris in the sediments is notable. It appears that environmental change brought in conditions suitable for the establishment of organic build-ups, although a difference in sediment provenance could also explain the facies change. The sequence at Millklint 1 indicates shallowing up through an inshore shelf area of carbonates, within wave base and coming into proximal environments.

The sequence through the uppermost beds of the Hemse Group in the eastern region also shows general increase in environmental energy. There is the widespread occurrence of many prominent skeletal layers which represent winnowed, current accumulations derived from large populations of opportunistic epifaunal brachiopods. Many carbonates in these higher beds show features of early lithification. The association of sediments in which there is local carbonate enrichment, nodular horizons and irregular layers of limestone suggests *in situ* submarine cementation, and it is evident from post-lithification suites of burrow traces that some cemented sheets of carbonate lay not far beneath the sediment surface (p. 12). Removal of soft surficial sediment leading to exposure of hard

substrates on the sea floor is indicated by beds with attached epifaunas and borings. Periods of strong scouring are demonstrated by eroded surfaces, and by intraformational conglomerates which result from exhumation of at least partially lithified sediment. In these conglomerates, hardground faunas established on intraclasts indicate that much reworked material was lithified prior to its redeposition. The wide, flat form of many clasts and their facies similarity to adjacent sediments (e.g. Botvide 1; p. 18) suggest fairly local derivation. It is apparent from the numerous depositional breaks and erosional episodes that net sedimentation was very slow and the sequences are condensed. The hardgrounds documented are certainly a minimum figure since the presence of encrusting faunas is usually evident only on weathered surfaces, and there are probably many minor breaks accompanied by little or no erosion, e.g. represented by winnowed skeletal deposits. The depositional environment appears to have been mainly below wave base although within the sphere of shoaling currents. The diverse, soft and hard bottom assemblages of benthic epifaunas suggest fairly shallow conditions. Intermittent conditions within wave base are indicated, for example, by beds with shallow symmetrical oscillation ripples at Häffride 2 (Fig. 2).

Nodule formation and early diagenetic hardening probably took place a little below the sediment-water interface, by analogy with Recent submarine cementation (e.g. nodule formation down to 32–75 cm: Mullins *et al.* 1980; cemented layers 5–50 cm below the surface: Taylor & Illing 1969). In the Qatar peninsula, thin irregular, lumpy limestone layers are produced by coalescence of nodules *in situ* in the near surface sediment (Shinn 1969). These sheets initially have irregular upper and lower surfaces but with continued cementation the upper limit becomes more level. When traced seawards, continuous limestone beds pass laterally into layers with separate cemented lumps, the early lithified horizons extending up to 75 km out into the Persian Gulf (Taylor & Illing 1969).

In offshore platform carbonates in the Bahamas, the formation of submarine cemented layers beneath a veneer of winnowed carbonate sand sediment was related by Mullins *et al.* (1979) to the presence of bottom currents strong enough to winnow out fine sediment. As well as increasing the permeability of the near-surface sediment by removal of fine material, the currents are important for creating pauses in deposition by erosion of unconsolidated sediment so that the exposure of layers at the sediment-water interface becomes prolonged; these factors accelerate submarine cementation (Mullins *et al.* 1980). Burrowing activity can also increase the permeability of the surface sediment to some extent. The offshore gradient from continuous layers to separate cemented lumps was attributed by Mullins *et al.* (1980), from investigations of carbonate slopes in the northern Bahamas, to a gradual decrease downslope in the strength of bottom currents. Shinn (1969) noted that areas of increased winnowing and lower sedimentation rate commonly coincide with breaks in slope. In modern settings, thin sequences with many lithified discontinuity surfaces are commonly associ-

ated with submarine seamounts and swells, and the shelf-slope break at continental margins (e.g. Gomberg 1973). Comparable environments are interpreted for condensed sequences in ancient carbonate sediments (e.g. Jenkyns 1971; Heckel 1972). For the Hemse Group, borehole sequences for the subsurface continuation down dip show a lateral transition into more offshore, fine-grained mudstones in which skeletal fossils are relatively few. However, there is no evidence of sediment instability to indicate an increased gradient of the slope, and a very gentle palaeoslope is inferred for the depositional basin (cf. also for Ordovician, Lindström 1963; Jaanusson 1961, 1973), without the marked break of slope which characterizes the edge of modern continental shelves.

Dolomitisation of sediments occurs at intermittent levels through limited intervals of the upper Hemse sequences at Botvide 1 and Gannor 1 (p. 11). It is probable that this is an early diagenetic feature, having taken place while the matrix was still relatively porous mud ("dolomitic mottling": e.g. Beales 1958; Larsen & Chilingar 1979). By comparison with adjacent sediments, faunas in the dolomitic beds are low in diversity and contain a prominent arthropod component (cf. Laporte 1971). There is no evidence for supratidal or evaporitic conditions, and a fairly restricted, subtidal environment with low agitation and aeration is probable (e.g. Andrichuk 1958; Füchtbauer 1974). The dolomitic intercalations among fine-grained sediments may therefore represent periods of reduced circulation, and perhaps lagoonal conditions locally. It is notable that Gotland lies not far from the secondary dolomitization front further north-east in the depositional basin (Kaljo 1970: 331); for example, Wenlock Jaagarahu beds (including reefs) in north-west Estonia are strongly dolomitized (Luha 1930).

At the Hemse-Eke boundary in the eastern region, the planed or irregular, mineralized surface, or mineralized zone of sediments, indicates further breaks in deposition with early lithification of beds. Evidence for a break is widespread, but from the variation in the detailed sequences across the boundary there is no reason to regard it as a single episode. Conglomerates and erosion surfaces within the lower part of the overlying Eke Formation indicate continued periodic scouring. Some strongly irregular erosion surfaces in the Eke carbonate sequences, which cut down locally to the mineralized Hemse strata, increase the facies complexity at the boundary level. The mineralization of the sediment appears to have taken place in submarine conditions, and probably during intervals of non-deposition. Glauconitization is restricted to lithified sediment in prolonged contact with sea water, while phosphatization takes place at slightly lower levels within the near surface sediment (Jarvis 1980). The pyritization is probably secondary, diagenetic reduction from limonite, occurring after further deposition of sediment rich in organic matter as a result of bacterial activity (Jaanusson 1973:25). Conglomeratic and pebbly deposits associated with the mineralized horizons contain many clasts which have encrusted surfaces, indicative of shallow marine reworking. The restriction of epizoans to relatively few of the mineralized beds may reflect

inhibition of organisms specific to carbonate substrates (Bromley 1975), although inadequate exposure may also be an explanation. Insufficient hardening is unlikely since mineralized horizons widely form the base level for later, Eke erosion and apparently prevented further downcutting apart from a few local, minor galleries (e.g. Fig. 2).

The overlying well-winnowed skeletal sands and biostromes of the Eke Formation carbonates, similar to those at Millklint 1, reflect very shallow, wave abraded environments. Locally there are small carbonate mounds, which occupied minor, isolated patches of the sea floor and did not contribute to any regional barrier structure. Overturned and broken skeletons of colonial organisms among the mounds indicate current disturbance, and the flanking, grain-supported crinoidal sands and gravels represent talus deposits of high energy environments. More sheltered areas of the inshore shelf environment are indicated by the carbonate sands and muds of the intermound sequences. In the eastern sections algal material in the sediments is mostly fragmental (apart from very local stromatolites), but on the outer edge of the tract with carbonate mounds, at Burgen 4 and Malms 1, there are lag deposits of "smooth" oncolites which formed in subtidal shoals. Commonly the oncolites occur in mud-supported sediments, but there are also some more extensively winnowed and reworked accumulations which reflect conditions of higher current energy. The oncolites with cryptalgal layering are replaced in higher beds, and laterally to the west, by *R. gotlandicum* oncolites; the latter characterize the shoal environments throughout the lower energy depositional areas represented by marl facies.

Over a limited part of the eastern outcrop area, subaerial karstic and tidal erosion are interpreted for extensive erosional networks cut in the lower Eke carbonates (Cherns 1982; p. 19). The base level of erosion is formed by the eroded, mineralized horizons at the top of the Hemse Group; the upper level cannot be traced in the limited exposure of higher beds but a minimum thickness of 6–7 m of strata includes similar erosion surfaces. Uplift and emersion of lithified Eke strata, with subsequent solution erosion and formation of tidal terraces, includes a wide area of inshore shelf carbonates (to as far west as Häffride 2), and must represent either the contemporary shoreline or emergence of a broad tract within the inshore shelf. At Nyan 4, the limited distribution of hardground faunas on the mineralized topmost Hemse surface shows that their establishment related to Eke erosion and not to the hiatus or multiple breaks at the end of Hemse deposition (p. 17). At Häffride 2, fractures across the mineralized top Hemse surface formed before epizoan encrustation and probably represent desiccation cracks from subaerial exposure (p. 17). This is the only definite evidence of emersion of the mineralized horizons; since also at this locality Eke erosion cuts down to the underlying Hemse sediments (Fig. 2), subaerial conditions may result from the later uplift and erosion. However, the close association of karst-eroded surfaces with mineralized Hemse levels may be an indication that some of

the latter became lithified in subaerial conditions. Jaanusson (1961) noted that in tropical and subtropical regions subaerial lithification is a very important process, and that the lack of features to indicate subaerial exposure (e.g. karst, desiccation structures) can be accounted for by subsequent tidal and intertidal scour, and biogenic modification. Also, since an extremely flat sea floor is supposed for the depositional basin, any erosion of an emergent land area would be minimal because of the limited vertical difference between the land surface and the base level of erosion, usually the groundwater level.

The cryptalgal limestones which are associated locally with the initial sedimentary infill of shallow marine carbonates upon the irregular Eke erosion surfaces form low domed, stromatolitic mounds (Cherns 1982). These are interpreted as establishing in shallow subtidal environments. Like the oncolites, the stromatolites include intergrowths of epizoic bryozoans among the algal fabric, indicative of rapid lithification of laminae and also denoting submarine environments. There is evidence of subaerial exposure only on the upper surfaces of the bodies, from desiccation features and borings. The stromatolites have a very limited distribution, confined to deposits on drowned relief of the karst-eroded, lithified limestones. This may reflect chiefly the absence of substrate disturbance by burrowing organisms, by contrast to the intense bioturbation typical of the oncolitic sequences (e.g. Gebelein 1969, 1976; Playford & Cockbain 1976; Playford 1980).

REGIONAL IMPLICATIONS

The depositional environments discussed are based upon the facies development, without implication that the deposits which occupy comparable positions within the regressive facies sequence are contemporaneous. The regional environmental changes taking place through the Hemse-Eke transition can be considered in terms of conditions across the strike with relation to the *lauensis-scissa* "time line" (p. 27). This runs from the upper Hemse limestones at Millklint 1 (taking *W. ludlowensis* as equivalent), through the upper Hemse sequences of the eastern region, the lower Eke Formation further west (e.g. Ronnings, Lingvide; Fig. 1), and then back into upper Hemse strata in the Burgsvik borehole (Fig. 1) sequence (e.g. Bassett *et al.*, 1981: fig. 8).

Taking beds slightly older than this, at Millklint 1 there are pelletal carbonate muds and sands laid down in relatively sheltered, shallow environments of inshore shelf areas where water was sufficiently warm for precipitation of calcium carbonate onto pelletal grains. In the eastern region, the sequences of carbonate and terrigenous muds, with some skeletal sands, indicate low to moderate energy shelf environments below wave base. Nodular carbonates and some local, thin, submarine-cemented sheets of limestone, which show early, submarine lithifica-

tion of sediments, probably reflect periods of slow net sedimentation together with some winnowing of the near surface sediment by bottom currents. To the west, there are well-bioturbated, less carbonate-rich sequences mainly of muds and silts, with generally sparser benthic faunas, deposited in low energy, offshore shelf areas. Further south, the sediments of the Burgsvik borehole (Hede 1919) are poorly fossiliferous offshore muds, mostly of low carbonate content although with some thin layers of carbonate-rich muds.

By the *lauensis-scissa* level there was a general overall increase in water energy that appears to represent shallowing of the depositional environments. In the northern area, there is a higher proportion of moderate to high energy carbonates, including well-winnowed, low diversity coquinas and shell banks among cross-bedded carbonate sands. These current influenced deposits indicate periods of stronger water energy in the areas within wave base in the inshore shelf suitable for formation of bahamitic limestones. The equivalent beds of eastern areas are condensed sequences of carbonate and terrigenous muds including prominent skeletal accumulations, and characterized by many interruptions in deposition. Periods of high water energy produced winnowed skeletal sands, and scoured, reworked and exposed lithified sediments on the sea floor where they became colonized by hardground faunas. Deposition took place in subtidal environments within the reach of shoaling currents, where widespread cementation of near surface sediment reflects the minimal net sedimentation rate in offshore areas, possibly swells, swept by gentle bottom currents. Intervals of lower water energy are indicated by deposition of muds, and locally there were periods of reduced circulation and perhaps lagoonal conditions. Mineralized horizons are a further indication of prolonged breaks in deposition, possibly with some emergence; some of these lithified layers have been modified by subsequent scour and by hard-bottom faunas. In the west this period covered the rapid transition from offshore shelf environments to inshore subtidal shoals where oncolites formed. Moderately agitated conditions indicated by the latter alternated with quieter water periods when muds and silts were deposited. At this level in the Burgsvik borehole sequence there are still low energy, offshore muds. In the vicinity of Ronnings (Fig. 1), Martinsson (1967:373) noted that *lauensis-scissa* marls strike directly into sandstones of the Burgsvik Formation. The clastic influx was derived from the west and north-west (Stel & de Coö 1977), and indicates regional uplift and erosion at this time.

Beds younger than the *lauensis-scissa* level show a continued increase in water energy across the outcrop area in response to further regional regression. Both in the northern and eastern areas these beds are lower Eke carbonates laid down in high energy, wave abraded environments of proximal parts of the inshore shelf and include biostromes and some small organic build-ups. Episodic scouring and reworking of sediments in the east, indicated by discordant erosion surfaces and by the lag conglomerates of the pebbly shale facies, widely also exhumed the top

beds of the underlying Hemse Group, down to mineralized sediment which formed a resistant horizon; this has the effect of accentuating the facies change at the boundary here. Emergence of a broad area of Eke carbonates at around this time in the east was followed by episodic karstic and tidal erosion. The regression was pulsatory; renewed submergence is indicated by the initial shallow marine infill onto the erosion surfaces, followed by subtidal establishment of stromatolites which became emergent at late stages (p. 39). Locally the Eke solution erosion also exposed mineralized Hemse horizons; in places there are subsequent hardground faunas on the latter, in one instance (Häffride 2) clearly later than subaerial emergence of mineralized sediments. At the outer edge of the high energy carbonate belt, shoal environments are indicated by oncolitic facies occurring as lag deposits among carbonate sands and muds. Shallow water, subtidal shoal environments covered a wide area. In the west and south, *Rothpletzella* oncolitic facies flank the tongue of nearshore clastic sediments represented by the lower Burgsvik Formation.

Variations in stratigraphy of sections studied, and the depositional environments inferred for the facies, make it probable that discontinuities are generally of very local significance, and even mineralized horizons do not represent synchronous levels across the outcrop area. The overlap between typically Hemse faunas and oncolitic facies in western sections (Fig. 2), and the continuation of Hemse sedimentation above mineralized levels before subsequent transition to oncolitic facies, e.g. at Malms 1, reflect transitional environmental change to Eke deposition. In the higher energy environments of eastern areas the facies change related to regional regression is pronounced both because of the condensed nature of Hemse sequences and from repeated erosional removal of younger sediments back down to lithified, mineralized horizons. The northern area has a relatively transitional boundary at the incoming of algal facies, albeit in high energy deposits and with some consequent slight erosional downcutting by the overlying, coarse-grained carbonates onto beds below. As discussed earlier, the absence of algal material from the Hemse sediments seems unlikely to relate solely to depth. The controlling factor is unknown, although possibly increased circulation and less muddy environments are important; facies of the Eke Formation are generally deposits of well-oxygenated, shallow marine environments.

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APPENDIX: DESCRIPTION OF NEW LOCALITIES

HÄFFRIDE 2, 635090 166555, c. 2580 m ENE of Burs church. Topographical map sheet 6J Roma SV. Geological map sheet Aa 156 Ronehamn.

Drainage ditch section running WNW–ESE through wooded land, c. 550 m N of L. Gläves. Also shallow irrigation ditches and loose material along fields bounding this woodland to W and SE.

Hemse Group and Eke Formation.

References: Cherns 1982.

HALLSARVE 3, 635442 167104, c. 1200 m ENE of Lau church. Topographical map sheet 6J Roma SV. Geological map sheet Aa 156 Ronehamn.

Bank section behind house, c. 20 m W of road.

Hemse Group and Eke Formation.

NYAN 4, 635375 167495, c. 5200 m ESE of Lau church. Topographical map sheet 6J Roma SV. Geological map sheet Aa 156 Ronehamn.

Shore exposures 0–150 m ENE from small jetty opposite isolated house at coast where road swings to E, and along to wall of small harbour at Nyudden.

Hemse Group and Eke Formation.

References: Cherns 1982; Munthe 1902: 44 and fig. 9 (also discussed by Manten 1971: 390–1).

STUMLE 2, 634375 165548, c. 1850 m SE of Alva church. Topographical map sheet 5I Hoburgen NO and 5J Hemse NV. Geological map sheet Aa 164 Hemse.

Shallow ditch section on E side of road and c. 70 m N of turning to Stumle.

Hemse Group and Eke Formation.

PRISKLASS D

Distribution

Liber Kartor

162 89 STOCKHOLM

Sveriges geologiska undersökning

Box 670

751 28 UPPSALA