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Stratigraphy of the Gorstian and Ludfordian (~~Middle~~ ~~mid~~upper Silurian) Hemse Group reefs on Gotland, Sweden~~.~~

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Abstract: The Hemse Group is one of the least understood stratigraphic units of the ~~whole~~ Silurian sequence of Gotland. New results from ~~airbourne~~airborne transient electromagnetic (ATEM) measurements ~~(EM)~~ in combination with ~~older~~ previously published data from field studies and geophysical investigations shed~~s~~ ~~some~~ new light ~~into~~ on ~~the~~ carbonate platform

development during the early to mid Ludlow Hemse Group.~~,~~ ATEM r~~development r~~evealsing a transgressive phase that begains ~~at~~ near the Wenlock-Ludlow boundary, which ~~event. This transgression is~~ ~~dominated~~ resulted in deposition ~~by~~ of marls and corresponds roughly to the ~~Ludlow~~ Hemse limestone units a-c ~~as well as~~and the ~~so-called~~Hemse Marl NW~~ phase~~. In this phase little or no reef development ~~seem to~~ occurs. The end of the transgressive phase ~~is correlated~~coincides ~~to~~ with the weak Linde ~~P/S event~~Event. The following highstand favoured extensive reef growth ~~secundo episode is interpreted as a highstand phase with extensive reef development~~ forming a reef barrier system of both fringing reefs and more rampiform settings with stromatoporoid biostromes and occasional biohermal buildups. The ~~well-known~~ Kuppen-Snabben Unconformity Complex~~Kuppen unconformity~~ marks an erosional (karstic) sequence boundary and rocky shoreline and the transition from a rampiform setting with reef biostromes towards a more rimmed setting with patch reefs.

Keywords: Unconformity, rocky shorelines, facies associations, ramps, Silurian, Gotland, geographic model.

The Hemse Group (Gp) (Gorstian-Ludfordian Stages, upper Silurian) on Gotland, Sweden, (Figs. 1-and 2) comprises a heterogeneous assemblage of carbonate facies (Sandström~~,~~ 1998). Reef-facies limestones occur in the eastern and central parts, and marls and claystones occur to the west and south (Fig. ~~2A~~2B). The limestone is currently subdivided into five informal units (Hede~~,~~ 1929, 1960) lettered from a to e (Laufeld 1974). Units a, b and lower parts of c are all assigned to the lower part (here called Hemse Transgressive Systems Tract (TST)), and upper parts of c together with d and e constitute the upper part (Hemse Highstand Systems Tract (HST)). Units c and d are the richest stromatoporoid-bearing units, and units c–e contain most of the biostromes, including the exposures studied here. To the west and south, the Hemse G~~rou~~p is represented by the Hemse marl NW (approximately Hemse TST), the Hemse marl SE (Hemse HST) and the topmost Hemse marl (probable sequence boundary; Hede 1960;~~,~~ Laufeld 1974).

The exposed sequence on Gotland is entirely Silurian and comprise approximately 750 meters of mainly limestones and marlstones, ranging from latest Te~~y~~lychian to the end-Ludfordian (Jeppsson 2005; Jeppsson et al. 2006). The strata are here divided into 13 lithostratigraphic f~~F~~ormations (Fm) and g~~G~~roups (Gp; cf. Fig. ~~1~~2; Hede 1960; Cherns 1983; Frykman 1989; Riding & Watts 1991; Long 1993; ~~Riding & Watts 1991, Hede 1960,~~ Calner 1999;~~,~~ Calner & Säll 1999;~~,~~ Calner et al. 2000;~~,~~ ~~Cherns 1983;~~ Eriksson & Calner 2008;~~-~~ ~~Frykman 1989;,~~ ~~Hede 1960;~~ Jeppsson 2005;~~,~~ ~~Cherns 1983, Eriksson & Calner 2008, Long 1993; Riding & Watts 1991~~). Gotland lithostratigraphy is still awaiting a more comprehensive revision, and some units are not well known lithostratigraphically (the Slite Gp and the Hemse Gp especially).

This paper aims to clarify the stratigraphic context of the Hemse G~~rou~~p reefal succession and discusses its sequence stratigraphical ~~importance~~ subdivision and relationship with event stratigraphy,~~in event- and sequence-stratigraphy~~ as well as the paleogeographic development of reef systems in the area.

Methods and terminology

In this paper, Dunham's (1962) expanded system of carbonate classification (cf. Flügel 2004, p 348-349) is used for determination of rock type. For the biostromes a classification scheme developed by Kershaw (1994) is used, that is ~~mainly~~ based mainly on the biostromes' taphonomic signature. Where applicable, we use Riding's (2002) terminology of reef types ~~used as suggested by Riding (2002)~~. Materials used are the results of mapping the coastal stretch between the Snabben ~~1~~ locality and the Sjaustrehammarn ~~4~~ locality as well as mapping of the inland central Hemse reef complex, stretching from west to east between Lindek ~~K~~lint and Torsburgen (Fig. ~~2~~3).

To give a comprehensive picture of the Hemse Gp reef development, results from several previous studies are used and compiled. The most important of these are by Manten (1971), Riding (1981), Kershaw (1981, 1990), Kano (1990), Keeling & Kershaw (1994), Sandström (1998, 2000), Sandström & Kershaw (2002, 2008), Samtleben et al. (2000), ~~Kano (1990), Flodén et al. (2001),~~ Bjerkéus & Eriksson (2001), Flodén et al. (2001), Erlström et al. (2009), and Erlström & Persson (2014)~~, Kershaw (1981, 1990), Keeling & Kershaw (1994), Riding (1981), Manten (1971) and Samtleben et al. (2000)~~.

To better connect field observations with regional scale reef development, new and compiled data from different regional and local geophysical measurements were obtained. The geophysical methods used are Airborne Transient ElectroMagnetic (ATEM)~~SkyTEM~~ (Dahlqvist et al 2015, 2017;~~,~~ Sørensen & Auken 2004), r~~R~~adiomagnetotellurics (RMT; Erlström & Persson 2014), airborne electromagnetic data (~~EM~~VLF, Erlström et al. 2009; Pedersen et al 2009) and off-shore seismic data (Flodén et al. 2001;~~,~~ Bjerkéus & Eriksson 2001). VLF is a frequency domain response technique that passively records signals of existing radio frequencies; ATEM is an active time domain response technique that uses the time a signal decays. ATEM yields results at depth, whilst VLF is suitable for surface coverage (cf. Legault 2015; Pedersen et al 2009).

The eastern Hemse biostrome complex

The area containing the strata studied ~~are~~is ~~area~~ defined by the Östergarn parish, which stretches from a line approximately defined from the Torsburgen cliff to the north down to the Sjaustrehammarn peninsula to the south and eastwards from this line to the coast at Herrvik and Kuppen (Fig. ~~2B~~3). Reef biostromes in this area are reported from Torsburgen (Manten 1971), Grogarnshuvud (Kershaw 1997;~~,~~ Sandström & Kershaw 2002, 2008), Kuppen (Kano 1990;~~,~~ Keeling & Kershaw 1994;~~,~~ Sandström & Kershaw 2002, 2008), Östergarn cliff (i.e Fakle locality; Sandström & Kershaw 2002, 2008) and Sjaustrehammarn (Kershaw 1994;~~,~~ Sandström & Kershaw 2002, 2008).

Sandström & Kershaw (2002) concluded that the biostromal complexes of the Hemse G~~rou~~p are subdivided into three main types: Kuppen-type and Grogarnshuvud~~-~~-type autoparabiostromes, and Sjaustrehammarn-type para/allobiostromes. Kuppen-type biostromes are characterized by densely packed stromatoporoid assemblages with stromatoporoid growth forms ranging from laminar to high and extended domical forms of Kershaw & Riding (1978). High-profile forms are commonly tilted; the matrix is composed of micrite together with layers of skeletal packstones and grainstones of mostly crinoids and stromatoporoid fragments. Grogarnshuvud-type biostromes are characterized by densely packed assemblages of mostly low-profile in situ stromatoporoids; the matrix consists of crinoid~~al~~ and stromatoporoid~~al~~ grainstones.

Sjaustrehammarn-type biostromes are made of reef rubble layers, in which dominant stromatoporoid morphologies are laminar to high and extended domical; the matrix consists of crinoid~~al~~ grainstones and stromatoporoid rudstones. Reef biostrome growth ~~are~~is favoured by stable skeletal substrates (Sandström & Kershaw 2002) and is probably a major control on their distribution and formation. Successive variations in relative sea level generated stacked biostromes separated by erosion surfaces and coarse bioclastic limestones (grainstones and rudstones). ~~Hurricanes and s~~Storms disrupted the internal structure of the biostromes ranging from autobiostromes and autoparabiostromes that were ~~mildly affected~~partly changed to para~~-~~bisotromes and allobiostromes where storms had a severe impact on the final appearance of the texture. Biologically the biostromes do not differ much (Sandström & Kershaw 2008); all are low-diversity assemblages dominated by four stromatoporoid species (*"Stromatopora" bekkeri, Plectostroma scaniense, Clathrodictyon mohicanum and Lophiostroma schmidti*).

The facies and the widespread low ~~-~~diversity of the biostromes reveal that there was a similar set of palaeoenvironmental conditions across the area where these biostromes crop out (Sandström & Kershaw 2008).

Stratigraphic relations of the biostromes are not investigated in detail. However, the very distinct Kuppen-Snabben Unconformity Complex ~~Kuppen unconformity~~ is traceable ~~over a large area~~for long ~~stretches~~distances in the southern parts of the area and is described by the Snabben unconformity association (see next ~~chapter~~section). ~~below.~~ ~~The~~ This unconformity has a few metres of relief and was described as a rocky shoreline ~~described from Kuppen (~~by Keeling & Kershaw (1994; see also field guide by Eriksson and Calner 2005). It is herein considered a ~~candidate for a major unconformal event, marking a probable~~major sequence boundary. The boundary is probably equivalent to the boundary described by Eriksson & Calner (2008) where the Kuppen-Snabben Unconformity Complex marks the onset of the FSST described by the Botvide member (sensu Jeppson 2005; Eriksson & Calner 2008).

Kuppen-Snabben Unconformity Complex~~Kuppen unconformity and Snabben association~~

The Kuppen-Snabben Unconformity Complex ~~Kuppen facies complex~~ is one of the most studied reef complexes on Gotland (Kano 1990;~~,~~ Kershaw 1981, 1990;~~,~~ Kershaw & Keeling 1994;~~,~~ Keeling & Kershaw 1994;~~,~~ Riding 1981;~~,~~ Sandström 2000;~~,~~ Sandström & Kershaw 1999, 2002, 2008). It comprises a set of stacked stromatoporoid reef biostromes with erosion surfaces and coarse bioclastic limestones in between, altogether making up a record of several small sea level fluctuations. One of the unconformities is extremely well developed and is referred to as the Kuppen unconformity (*sensu* Keeling & Kershaw 1994). However, several phases of rocky shore development occurred (Keeling & Kershaw 1994) with low relief palaeo–sea stacks and conglomerates as the most visible evidence. Close to the small sea stack of locality Snabben 1, that forms a tiny outlier, directly south of the Kuppen localities, an association is seen that is here used to track ~~the~~ this complex of unconformitiesy over a larger area (Figs. ~~3~~4, ~~4A~~5A). The association is in the text referred as the Snabben unconformity association and consist of mainly three characteristics:

1. Reef limestone draped by conglomerates (Fig. ~~4~~5. A-G). The reef limestones are stromatoporoid rich and show a bafflestone to floatstone character. Conglomerates consist of stromatoporoid clasts, often elongated and abraded and are sometimes orientated (cf. Manten 1971).
2. Truncated fossil allochems (Fig. ~~4~~5~~.~~ C, D and G). The reef limestone is eroded at its top, which is mostly seen as a truncation of stromatoporoids and other reef organisms.
3. Orientated ridges. At Snabben ~~1~~ and in other areas, the association is displayed as oriented elongated ridges measuring 1-2 m wide, c. 1 m in height with a length of up to tens of meters (Figs. ~~3~~ 4 and ~~4~~5). These ridges run in an approximate N-S direction except for the southernmost part of the Sysne peninsula where directions seem to be random.

Using these three criteria the Snabben unconformity association was traced for several kilometres southwards along the SE Gotland coastline (cf. Fig. ~~3~~4), thus connecting this regressive event with inner- to at least mid-ramp facies.

The ~~stretch~~ section between Snabben and the Sysne peninsula

This part of the mapped area is characterised by coarse bioclastic limestones ranging from grainstones to conglomerates. Thin autopara-biostromes, para-biostromes and allobiostromes are present, and in some of these are clear evidence of unconformable events, where the ~~criterions~~characteristics 1 and 2 ~~were~~ are always present, and where exposure was large enough for ~~criterion~~ character 3 ~~could~~ to be ~~detected~~observed. At the top of the autoparabiostromes truncated stromatoporoids are common and draped by pebble conglomerates of flattened, elongated 1-~~1~~—10 cm large stromatoporoid pebbles, displaying a high degree of roundness, in a grainstone matrix.

The Sysne peninsula

The e~~E~~astern part of the Sysne peninsula is characterised by patches of reef limestone, of autoparabiostrome character, surrounded by beach-face pebble conglomerates and very coarse bioclastic rudstones. The pebble conglomerate ~~is~~ dips ~~inping at~~ all directions and the surface is highly undulating and ~~seems to~~may follow an underlying topography, thus ~~one might suspect~~indicating a possible~~n~~ erosive event prior to the forming of the conglomerates. In only a few places, the unconformity association is clearly seen~~, and these occurrences enhance the idea of lower truncated reef limestones~~.

In the SE-most part of the peninsula, the association is again clearly seen and crops out in several places along the shore. Here, shales ~~are~~ drape~~ing~~ the reef limestones, supporting the idea ~~for~~ that the whole eastern part of the peninsula represents the Kuppen-Snabben U~~u~~nconformity Complex~~association~~.

Sysne – Sjaustrehammarn

From Sysne and southwards several small ~~points~~ outcrops display stromatoporoid~~-~~-rich limestones where ~~categories~~ characters 1 and 2 are clearly recognised, and in two places, character 3 (parallel ridges) are present (Fig. ~~3~~4).

~~Beyond~~ South of the biostromal facies association

South of Sjaustrehammarn no large enough outcrops are present for several km. At Ljugarn and Folhammar (Fig. ~~2B~~3), reef limestones are present, but their lateral connection to the Östergarn biostromes is not established. Earlier investigations on the Folhammar outcrops have revealed unconformities (Kano 1990) and vadose sediments (Sandström 1998). Riding (1981) also ~~suggest~~ interpreted a very shallow nature for these reefal deposits.

The central Hemse reef complex

The central part of the Hemse Gp~~,~~ ~~yields~~ comprises limestones with general facies of grainstones in the northern part, coupled with ~~occasional~~ uncommon marlstones and limestone/marlstone alterations. In t~~T~~he southern portion of the central part, –limestones are reef dominated, and ~~outcrops as~~form ~~present-day inland cliffs, forming~~ a band of cliffs that can be traced eastwards to the coast, cropping out at the Ljugarn and Folhammarn coastal areas. The inland cliffs are little known and very few studies have been made on the sedimentology and depositional history of these. Manten (1971) ~~gives a description and~~presented an overview of the different reef types~~ occurring~~. ~~In this paper~~Below a general description of the reefs and facies relations from some of the outcrops ~~are ~~is presented.

The Lindeklint reef

Lindeklint is the ~~most western of the~~westernmost reef~~s~~ outcrop~~ping~~ in the central part of the Hemse Gp (Fig. ~~2B~~3) The lower part of the cliff consists of a 2-~~-~~m-thick coarse crinoid grain/rudstone unit, followed by a ca 2-2.~~,~~5 m thick ~~layer ~~unit of detrital, mostly domical stromatoproids and coarse crinoidal fragments, indicating a proximal fore-reef talus. On top of this is a 4 m thick unit of reef limestones of laminar and anastomosing *in-situ* stromatoporoids and occasional over-turned ~~over ~~domical stromatoporoids. This facies intercalates with coarse crinoidal grainstone shoals and corresponds to shallow reef facies similar to the outcrops at Folhammar (Kano 1990;~~,~~ Sandström 1998).

The ~~stretch ~~section between Lindeklint and Ljugarn

Facies across the stretch between Lindeklint and Ljugarn/Folhammar are similar and the description for the Lindeklint succession is a good general example. A few localities in the northern part of this reef belt ~~outcrops ~~contain facies that are more like the eastern Kuppen facies complex. For instance, at Asträsk, ~~one can find~~are the same facies associations that are described from the ~~Kuppen and Snabben outliers~~Kuppen-Snabben Unconformity Complex; a~~A~~ series of stacked autoparabiostromes, 1-1.~~,~~5 m thick, separated by erosion surfaces are visible at the cliff-face. On top of the cliff are several elongated ridges stretched in a SW-NE direction, ~~very like~~like the ridges found at Snabben.

~~At ~~In the Lojsta area (Rammträsk and Broträskkröken; Fig. ~~2B~~3), a large complex of inland cliffs faces ~~is facing~~ north with lakes at the end of the cliffs. The facies and succession, where readily accessible, ~~seems to be~~are interpreted as equivalent to the Lindeklint facies succession. About 400 m south of the eastern lake, Broträskkröken, a 2 m high cliff is visible for about 20 metres. This outcrop consists of three units of crossbedded, very coarse crinoid grainstones separated by sorted fine-grained, silt-sized grainstones. In the coarse units, larger debris of ~~what seems to be~~ laminar stromatoporoids are common.

Ljugarn and Folhammarn area

Ca 3.~~,~~5 km NNW of Ljugarn village is an abandoned quarry called Rudvier (Fig. ~~2B~~3) where 10-12 meters of coarse crinoid grainstones intercalated with biostromal and biohermal patches of reef boundstones crop out. The exposed sequence shows a succession of three ~~facies~~ units; a lower unit of ca 1 meter of argillaceous limestones and marlstones (packstones) followed by an upper unit ~~of~~ 5-6 meters thick of coarse bioclastic grainstones. The uppermost unit shows stromatoporoid autoparabiostromes and patchy bioherms with intercalated bioclastic detrital grainstones. Kano (1990) made a thorough description of the stromatoporoids belonging to the biostromes and the argillaceous lower unit. In the ~~argillaceous lower unit~~latter, laminar and low domical stromatoporoids are mostly *in-situ* and high domical and bulbous forms are overturned. The fine-grained matrix (packstones) together with mostly in-place macro-organisms ~~suggest~~ are evidence of a low to moderate energy environment for this unit. The following unit of bioclastic grainstones contains mostly coarse debris of reef constructors dominated by crin~~i~~oid stem parts and stromatoporoid fragments, indicating high energy ~~environments~~events. The biostromal/biohermal reef unit on top of the sequence ~~is again~~was also deposited in a less turbid environment and the texture of the reefs ~~are~~ is similar to the Kuppen peninsula biostromes. The biostromes are autoparabiostromes with low domical forms *in-situ* and high forms overturned. The stromatoporoids are dominated by high domical and extended domical forms not in place. Only a minor part is of low domical and laminar forms of which most are in-place making this a Kuppen-type autoparabiostrome (*sensu* Sandström & Kershaw 2002; cf ~~Figs~~figs. 5 and 6 in Kano 1990). This unit is ~~probably~~ interpreted ~~deposited~~ as having formed in a low energy environment, affected by episodic storms that overturn the high stromatoporoids (see Sandström & Kershaw 2002, 2008 for an explanation of the dynamics and interpretation of the formation of autoparabiostromes).

The coastal stretch from Ljugarn to Folhammarn reveals sea-stacks rich in stromatoporoid reef facies. The Folhammarn is a nature reserve where sea-stacks occur densely and gives an opportunity to see the reefal nature of the bedrock in detail. This nature reserve has been thoroughly described and analysed by Kano (1990) and later by Sandström (1998). Sandström (1998) distinguished four different reef facies: L~~l~~arge stromatoporoid packstones (LP), anastomosing and laminar stromatoporoid packstones (ALP), favositid/stromatoporoid grainstones (FG) and detrital grainstones and rudstones (DG).

The stromatoporoid fauna of Folhammarn is dominated by *Parallelostroma typicum* and is considered a low diversity assemblage. Stromatoporoid morphotypes differ significantly between units and is probably due to differences in the sedimentary pattern as well as wave energy~~ (stress)~~. Very large stromatoporoids (>1 m in base) show signs of a two-stage growth, beginning with a lateral mode of growth interrupted by episodic sedimentation followed by a second stage with vertical growth and non-overlapping laminae (Sandström 1998).

Geographically, the Folhammarn complex was marine and is interpreted to have been ~~protected~~ an area of relatively low energy, thus likely ~~and~~ situated not far from shore, although it is not ~~to be considered~~ lagoonal. Occurrence of vadose silt in the ALP-unit suggests a subaerial contact at the top of the unit or above (Sandström 1998). Hard substrates for stromatoporoid growth are evidence of early sea-floor cementation~~Hard substrates for stromatoporoid growth may have been provided by microbial cementation~~ instead of earlier ~~suggested~~ interpreted karstic processes (cf. Kano 1990, 1994). Sedimentation rates were low in general, but the influence of storms ~~and hurricanes~~ yielded episodic pulses of high sedimentation indicated by the ragged margins and sediment inclusions of the stromatoporoid skeletons.

Geophysical investigations~~s~~

Airborne Transient ElectroMagnetics (ATEM)~~Sky TEM~~

~~Sky~~ ATEM measurements were made in 2013 and 2015 as a part of a comprehensive program to find suitable water reservoirs on ~~the island~~ Gotland (Dahlqvist et al. 2015, 2017;~~,~~ Jørgensen et al. 2018). Parts of these measurements ~~continued into~~derive from the Hemse Gp outcrop area although most ~~results~~ are ~~on~~ from other areas and units of the island. For this study, four profiles of good signal quality and with the best coverage of the Hemse Gp area ~~was~~ were chosen to ~~illustrate~~ add data to the ~~dynamics and formation of the unit~~subsurface geology and stratigraphy (see Fig. ~~5~~ 6 for the geographical position of each profile).

The profiles are together a good example of the ~~nature~~ depositional dynamics of the Hemse Gp platform ~~dynamics~~. Profile A ~~stretch~~ is orientated W-E and shows a cross section of the inland cliff area of the central Hemse Reef Complex described ~~previously in this article~~above. Profiles B and C ~~stretch perpendicular~~are orientated in a roughly N-S direction. These profiles connect the reef area with the När Fm and the ~~- following unconformal~~overlying unconformity marking the Hemse-Eke boundary. Profile D is to the NW of the Central Hemse Reef Complex and illustrates a N-S profile of the Klinteberg Fm and the Hemse marl NE.

Profile A (Fig. ~~5~~6) runs along the central reef barrier area. ~~The lower middle part is equivalent to the transgressive system tracts~~ The upper part reveals extensive reef development along the whole line with early development of aggrading reef build-ups as biohermal patch reefs. Unfortunately, modern erosion probably has taken away the uppermost parts of the sequence and whether the reefs developed into biostromal shapes is not clear here.

Profiles B and C (Fig. 56) runs perpendicular to profile A and shows the southward sloping carbonate ramp system. The dDepositional environment for the Hemse group Gp (i.e Wenlock/Ludlow boundary and onwards) probably reflectsis interpreted as –a transgressive systems tract followed by a highstand situation of a prograding carbonate ramp/barrier with several minor regressive/transgressive stages (as seen in outcrops). At its most southern parts, marked by question-marks in the profile, a regression is seen in outcrops from the area of very shallow carbonates (oolites, karstic features and few reefs as well as the formation of oncolitic fine-grained limestones), consistent with a making the sequence boundary to the Eke Fm (Cherns 1982, 1983,. 1999;, Jeppsson et al. 2007;, Eriksson & Calner 2008).

Profile D (Fig. 56) exemplifies a more distal part of the platform and here the Wenlock-Ludlow boundary is not as clear as for the other profiles. However, the boundary is evident with a development from a carbonate ramp to a transgressive phase with marly limestones and gradually becoming a marlstoneclay-rich limestone– (i.e. Hemse mMarl NWE).

Seismic profiless

Seismic investigations of the bedrock east and south-east of the Grogarn peninsula reveal that the Hemse reefs are a part of an extensive reef barrier tract system (Flodén et al. 2001;, cf. Fig. 2C3B). Depending on topography (rampiform or fringing) along the barrier transects bioherms and biostromes have formed. Thus, there are not only temporal variations of the types of reefs developed, but also a lateral shift making the architecture of the platform shift between low-angle ramps and more pronounced rimmed settings. Tuuling & Flodén (2013) showed interpreted the seismic correlation of the Silurian sequencessuccessions between Gotland and Saaremaa. The overall Silurian platform architecture of the whole Gotland sequence may be divided into aggrading (Llandovery-early Wenlock), prograding and regressive (early-mid Wenlock), prograding-regressive-transgressive (late Wenlock-mid-Ludlow) and regressive-transgressive (late Ludlow). The Hemse Gp development is marked characterized by a platform development resulting from long-term infilling of the Baltic Bbasin, continuously narrowing the available space for reef growth. The result is a trend towards rampiform settings with shoals and biostromal "stromatoporoid carpets" becoming increasingly abundant (cf. Tuuling & Flodén 2013, Sandström & Kershaw 2002, 2008). This is especially noted in the late Wenlock to Ludlow sequencessuccessions in the eastern parts of the basin in Saaremaa, Estonia and off-shore adjacent areas (Tuuling & Flodén 2011).

Airborne EM (VLF)

The data from airborne Very Low Frequency (VLF) measurements very clearly distinguishes between reefs, limestones and marls (Fig. 2C3B). There is a clear borderlinetransition between the Wenlock Klinteberg Fm (Wenlock) and the Ludlow Hemse Gp, probably marking a shift to a lowstand situation (Ludlow). .Directly SE of the line transition the transgressive system is visible with argillaceous marly sedimentation, followed by a marked reef development in the mid Homerian Gorstian highstand (Linde Event). Progradation of the Hemse group Gp reefs and platform carbonates continued until the topmost part of the Hemse Gp where yet another shift to argillaceous and algal limestones occur and marks the initiation of the Lau Eevent (tTopmost Hemse marl; see Jeppsson et al. 2007; Eriksson & Calner 2008; Younes et al. 2017). The occurrence of reefs from the VLF measurements correlates well with the interpreted reef barrier systems from the seismic studies (Fig. 2C3B) and the results from Sky ATEM and RMT measurements as well as field observations. Thus, these indications allow for a more comprehensive interpretation of the Hemse reef development as discussed below.

Remanent Magnetotellurics (RMT)

Ground RMT measurements was undertaken as a part of testing and validating the techniques, used~~s~~ as a tool for measuring different geological environments (Erlstöm & Persson 2014). The results from these tests confirmed a period of low reef growth ~~just after~~above the Wenlock-Ludlow ~~border~~boundary. This was followed by a transgressive phase of marly limestones and marlstones, where the reef development follows the same pattern as is shown by the results from ~~SkyTEM~~ ATEM measurements.

Discussion

Topography, facies and ~~a~~ palaeogeography~~ic proposal~~

All biostromes present in the e~~E~~astern Hemse Gr~~ou~~p are represented as topographic highs (cliffs, klints and sea stack areas) in the present-day landscape. The apparent lack of faulting in the area and previous investigations all has shown that the biostromes had enough relief to produce a rocky coast with sea stacks and topography (Keeling & Kershaw 1994), the present highs may well represent past patches of small ~~sponge~~ islands of calcified sponge buildups, much like back barrier patch reefs develop into temporary islands during periods of low sea level (cf. G~~g~~reat B~~b~~arrier R~~r~~eef, Australia and the barrier reefs at Belize; Burke et al. 1998; Huchings et al. 2009). Such a model ~~suggest~~ proposes that the Eastern Hemse Gr~~ou~~p limestone sequence was built up by several laterally-~~-~~extensive elongated to circular, low relief ~~patch reefs~~ biostromal reefs, that during low sea level occasionally formed small islands with rocky shores and small coastal cliffs. These ~~patch reefs~~ biostromal patch reefs were separated by inter~~-~~-reef grainstone shoals and marly limestones. To the north and/or NW was the hinterland, ~~and~~ whereas the deeper basin was situated to the south and southeast~~subsequently we had deeper settings to the S and SE~~, ~~and is~~as represented by the Hemse marl SE. Flodén et al. (2001) recognised a seismic barrier system east of the Gotland coastline that is linked to the Hemse reef units, suggesting that the Hemse reefs are a part of a ~~longer~~ larger system of ~~patch reefs~~buildups forming ~~a widespread and~~an elongated narrow ~~barrier~~ system stretching ENE – WSW.

Sandström & Kershaw (2002) discussed two different settings for the Hemse biostromal complexes; one model ~~suggests~~ proposed a semi-sheltered extensive and shallow back barrier environment with its approximate modern equivalent in the Belize reef barrier system (sensu Burke et al. 1998). The second ~~suggestion~~ interpretation is an open and homoclinal ramp environment where the degree of exposure is represented by the taphonomic effects ranging from autoparabiostromes in more sheltered and leeward areas to para-biostromes and allobiostromes ~~on~~ in very exposed parts. The results from Flodén et al. (2001) together with conclusions from this study ~~seem to~~ support both alternatives, where development goes from the second alternative to the first and where the Kuppen unconforma~~ble~~l ~~event~~ surface marks a transition from an open homoclinal ramp to more barrier-like settings.

The stratigraphic nature of the Hemse Gp reefal succession and development

~~Based on some general principles from the earlier barrier complex of the early to mid-Wenlock development in the northern part of Gotland, a general~~The succession of different reef types may be ~~coupled~~ linked to a sequence stratigraphic context following some general principles based on studies from the earlier barrier complex of the early to mid-Wenlock development in the northern part of Gotland (cf. ~~Sandström 2000,~~ Riding 1981, Watts & Riding 2000, Sandström 2000). D~~The general rule is that d~~uring a transgression ~~ve system~~

~~tract~~ reefs ~~will~~ developed as bioherms ~~and have~~with ~~columnar~~ vertically extended shapes, like the Wenlock reef bodies of the NW coast of Gotland (Watts & Riding 2000). In contrast, when the transgression reaches its highstand, ~~During a high stand systems tract,~~ reefs ~~will~~ lack the accommodation space to continue to grow vertically, and instead develop more laterally, ~~and~~ eventually form biostromal shapes as seen on top of the Wenlock Högklint reefs (Watts & Riding 2000). A schematic sketch of such a development ~~was outlined~~ by Sandström (2000) ~~and it may still~~ forms a general model for the reef development in the Silurian of the Baltic craton. Comparing the model to the development of the Hemse Gp reefs shows a somewhat different picture (Fig. ~~6~~7). The Wenlock/Ludlow ~~border~~ boundary interval is here marked by an erosional ~~scar~~unconformity~~,~~ that gives significant evidence of subaerial exposure of a reef tract belonging to the Klinteberg Formation (Eriksson 2004). ~~After this a transgression occurred, yielding erosive rocky shorelines~~ Basinward, bioclastic shoals of coarse grainstones, grading with depth into marls and packstones. During the transgressive phase, there seem to have been little or no development of reefs like the Högklint Fm in the Wenlock. Instead the shift to reef growth seems to take place after maximum flooding, or during the late stages of the transgressive phase, and then it developed as laterally extensive stromatoporoid biostromes. The nature of the HST or late TST ~~seems to be as~~is consistent with interpretation of a series of episodic small transgressions followed by lateral expansions and minor regressions forming rocky shorelines and conglomerates.

The Kuppen-Snabben U~~u~~nconformity C~~c~~omplex ~~Kuppen unconformity~~ is a more severe regression that ~~probably my have~~ affected ~~the entire~~a large area of the Hemse Gp carbonate platform. After this regression, ~~a more ‘normal’~~ development into a ~~biohermal~~ barrier with back reef biostromes and patch reefs occurred during the later phase of the Hemse reef development. The transgressive ~~or maybe actually low-stand~~ phase in the early part of the Hemse Gp coincides with Sproge ~~primo~~ Primo ~~episode~~ Episode (sensu Jeppson et al. 2006).~~,~~

and the transition to the reef development phase is coherent with the Linde ~~extinction~~ Extinction ~~event~~Event (Jeppsson & Aldridge 2000). The reef developing biostromal period is equivalent to the Etelhem ~~secundo~~ Secundo ~~episode~~Episode. The Kuppen-Snabben U~~u~~nconformity C~~c~~omplex ~~Kuppen unconformal event~~ is however, not recognised by Jeppsson et al. (2006) more than its position is marked by question marks. Thus, ~~this event~~thes~~s~~ potential impact of this lowstand of sea-level and exposure of the platform on the ~~biology~~ marine fauna is not ~~very~~ known. ~~, and it most probably did not exist last veryfor long.~~

~~Looking at the chemical record,~~ Stable carbon ~~isotopic~~ isotope stratigraphy ~~signals are~~is ~~very~~ little investigated and ambiguous for the Linde ~~event~~Event, with a ~~minor~~ weak ~~dip~~ positive shift in ~~the~~ δ~~d~~^{13}C ~~curve~~ (Samtleben et al. 2000). For the top part of the Etelhem ~~secundo~~ Secundo ~~episode~~ Episode that marks the probable Kuppen-Snabben U~~u~~nconformity C~~c~~omplex~~Kuppen event~~, no apparent isotopic changes take place (cf. Samtleben et al. 2000; Jeppsson et al. 2007~~; Samtleben et al. 2000~~). The conclusion is that the Linde ~~event~~ Event is a clear Primo-Secundo ~~event~~Event, although not as severe as ~~its~~ the more famous Ireviken ~~event~~ ~~Event~~ and Lau ~~event~~Events. The following Lau ~~event~~ Event (Jeppsson et al. 2007, ~~Younes et al 2017,~~ Bowman et al. 2019) shows a rapid and ~~major increase~~~~strong~~ positive increase in ~~the~~ δ^{13}C, reaching above 9‰ on Gotland (Younes et al. 2017)~~d13C,~~. ~~the~~ The Linde ~~event~~ Event shows a distinct but much less dramatic increase in δ^{13}C values (Samtleben et al. 2000).

Conclusions

- New data from geophysical ATEM measurements, together with previously published and unpublished geophysical and field data reveal new insights to the Hemse Gp carbonate system. The ~~early~~ lower Hemse Group (Ludlow, Silurian) on Gotland

~~developed as a~~represents a transgressive systems tract, and thus the initiation of a carbonate platform cycle –with deposition of marls and no or very limited reef growth. The end of the transgression, and thus maximum flooding of the basin within this sequence cycle, coincides with the Linde ~~P/S~~Primo-Secundo E~~e~~vent and marks the transition to a highstand systems tract ~~of a~~with a strongly prograding ~~carbonate platform forming a~~ barrier reef system.

- The Östergarn reef tract (sensu Flodén et al. 2001) shows a lateral ~~shift~~ transition from a typical barrier reef to the west and east of the Östergarn peninsula to a more rampiform setting at the actual Östergarn area (easternmost part of the Hemse ~~Fm~~ Gp onshore Gotland). ~~There are indications of barrier reef settings in front of the ramp environment.~~ ~~This is mostly based on the extension of the lineament of the magnetic measurements from Erlström et al. (2009).~~
- ~~The Kuppen Unconformity consist of several minor~~ and at least one major ~~erosive events and at least one major, that has influenced the upper~~ inner ~~– and mid- ramp environments.~~ A facies association typical for the Kuppen-Snabben U~~u~~nconformity C~~c~~omplex ~~major unconformal event~~~~associated lowstand~~ is recognised over a large area and contributes significantly to the ~~above stated~~interpretation that these erosive events ~~has~~ influenced the inner, mid and outer ramp environments.~~-~~
- The laterally extensive biostromal patch reefs ~~exposed proliferation~~system is significantly different from surrounding intra-~~-~~reef areas and did probably form small islands during ~~daily~~ lowstand periods.

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Figures:

Figure 1. Map of Scandinavia and the East Baltic area showing the position of Gotland (within the box) as well as the ~~Gotland showing the lithostratigraphic untis~~units ~~highlighting the Hemse Group. Upper left inset shows the~~ paleogeographical setting for Gotland and the Baltic Basin during the mid-Silurian~~.~~ (~~Modified~~ modified from Baarli et al 2003~~,~~; Eriksson &

Calner 2008). ~~Lower left inset shows the area where SkyTEM~~ ATEM ~~measurements were made during the years 2014-2015 (light gray), the profiles used in this paper (black lines) and the area enlarged in figure 2B (black box).~~

Figure 2. The stratigraphy and overall facies distribution of Gotland. **A**. Map showing the main stratigraphic units of Gotland. ~~A~~**B**. ~~Map of Gotland showing the main~~Large-scale facies distribution of the Silurian bedrock~~.~~ ~~White = limestones; Gary~~ ~~Gray~~ ~~= marlstone; Light gray = sand- and siltstone; Black = reef limestones.~~ (~~Modified~~ modified from Sandström 1998). ~~**B**. Map of the eastern part of the Hemse Group showing the main localities. Dotted lines indicate the outline of the Hemse Group. **C**. Map of the easternmost part of Gotland showing the airbourne~~~~airborne~~ ~~VLF and its correlation with reef barriers in the Baltic sea interpreted from seismic masurements~~~~measurements~~ ~~(from Flodén et al. 2001).~~

Figure 3. **A**. Map of the eastern part of the Hemse Group showing main localities discussed herein. Black dotted line shows the Klinteberg Formation-Hemse Group boundary. Grey dotted lines show erosional outliers. **B**. Map of the same area as in 3A showing the airborne VLF and its correlation with major barrier reef tracts in the Baltic sea as previously interpreted from seismic stratigraphy (from Flodén et al. 2001).

Figure ~~3~~4. Map of the stretch from Kuppen to Sjaustrehammar, revealing the observed ~~feauters~~features of the Kuppen-S~~b~~nabben ~~unconformal facies associations~~U~~u~~nconformity Complex and associated facies. Black = reef facies; gray ~~s~~= conglomerates; * = association (as described by the inset figure); ? = uncertain association; ¤ = erosional potholes (Silurian ~~karsts~~karst weathering); rose diagrams refer to the orientation of the axes of ridges as exemplified by the inset. The typical features of the association are shown by the inset and described in the text. Photographs of the different association features are ~~examplified~~exemplified in Fig. ~~4~~5.

Figure ~~4~~5. Examples of the ~~unconformal~~ Snabben unconformity association ~~and karstic associations~~associated karst found between Kuppen and Sjaustrehammarn. **A**. Type area for the association at Snabben. **B**. Flank sediments draping a reef ridge (Gryngudd). **C**, **D**. Conglomerates cutting truncated stromatoporoids (along the stretch between Snabben and Sysneudd). **E**. Conglomeratic shales draping reef facies (along the stretch between Sysneudd and Gryngudd) **F**. Conglomerates (left) intercalating with reef facies (right; close to Sjaustrehammar). **G**. ~~Congolmeratic~~Conglomeratic shales on truncated stromatoporoids (reef facies; Sysneudd). **H**. Potholes (karst~~s~~) filled with stromatoporoid floatstones (Sysneudd).

Figure ~~5~~6. ~~Sky~~ ATEM profiles across the Hemse Gp outcrop area with the Wenlock-Ludlow boundary (W/L) indicated as well as the overlying strata, herein interpreted as belonging to the transgressive (TST) and highstand (HST) systems tracts. ~~showing the depositional dynamics of the Wenlock-Ludlow boundary (W/L) and the following transgressive phase (TST), that further shifts to a highstand (HST).~~ The boundary between ~~TST and HST~~the two systems tracts, i.e. the maximum flooding surface (MFS) marks the approximate position for the Linde ~~P/S~~Primo-Secundo ~~event~~Event. ?? = –Uncertain. Lower right map inset shows the area where ATEM measurements were made during the years 2014-2015 (light gray) and the specific profiles used in this paper (black lines).

Figure ~~6~~7. Diagram of the ~~suggested~~ interpreted sequence for the Hemse Group reef development.

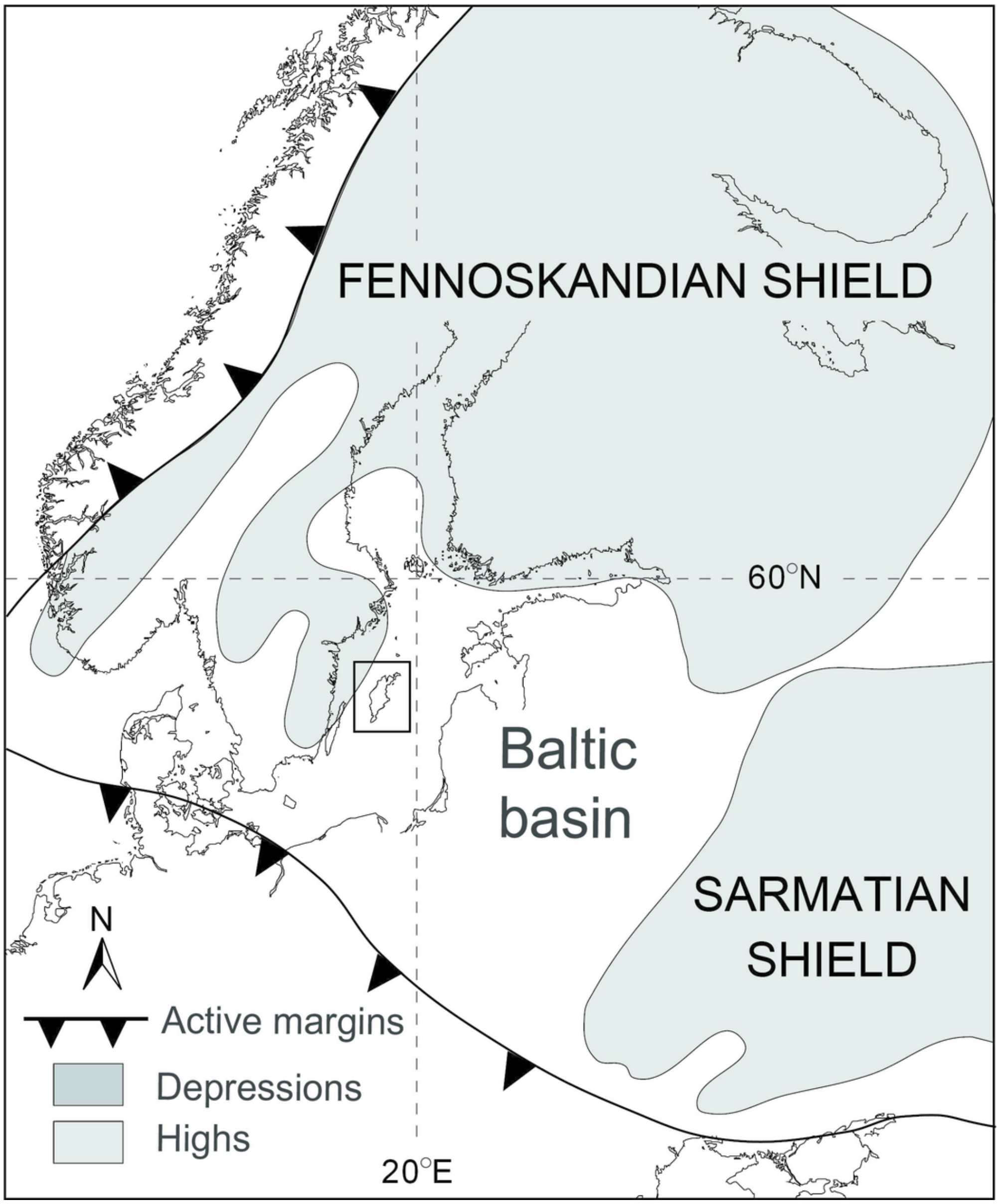

Figure 1. Map of Scandinavia and the East Baltic area showing the position of Gotland (within the box) as well as the paleogeographical setting for Gotland and the Baltic Basin during the mid-Silurian (modified from Baarli et al 2003; Eriksson & Calner 2008).

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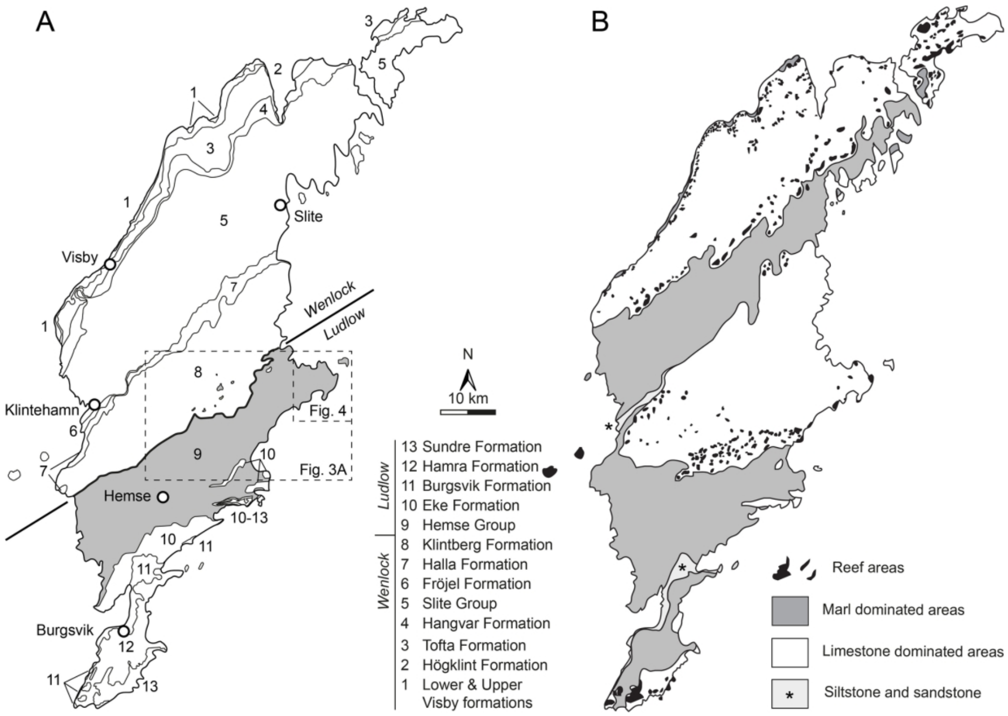

Figure 2. The stratigraphy and overall facies distribution of Gotland. A. Map showing the main stratigraphic units of Gotland. B. Large-scale facies distribution of the Silurian bedrock (modified from Sandström 1998).

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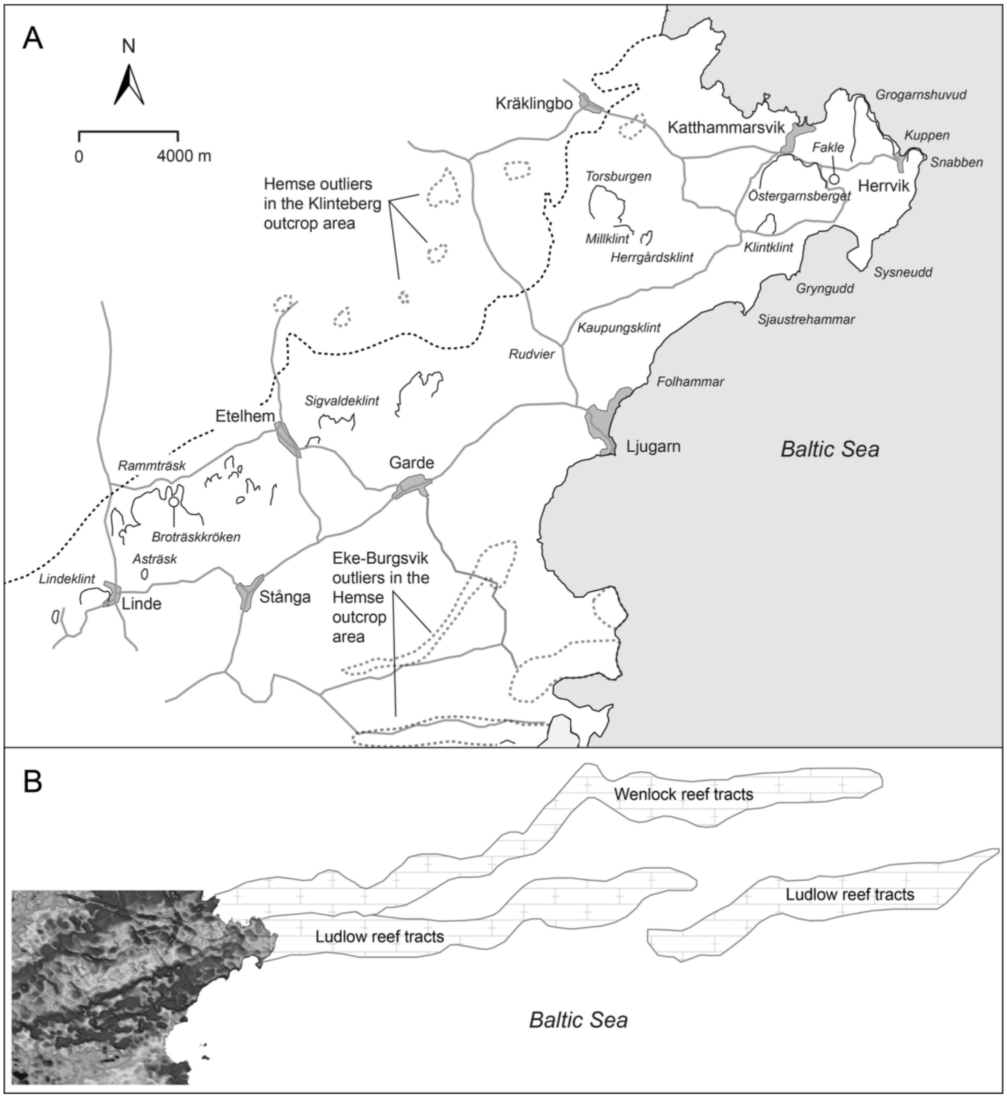

Figure 3. A. Map of the eastern part of the Hemse Group showing main localities discussed herein. Black dotted line shows the Klinteberg Formation-Hemse Group boundary. Grey dotted lines show erosional outliers. B. Map of the same area as in 3A showing the airborne VLF and its correlation with major barrier reef tracts in the Baltic sea as previously interpreted from seismic stratigraphy (from Flodén et al. 2001).

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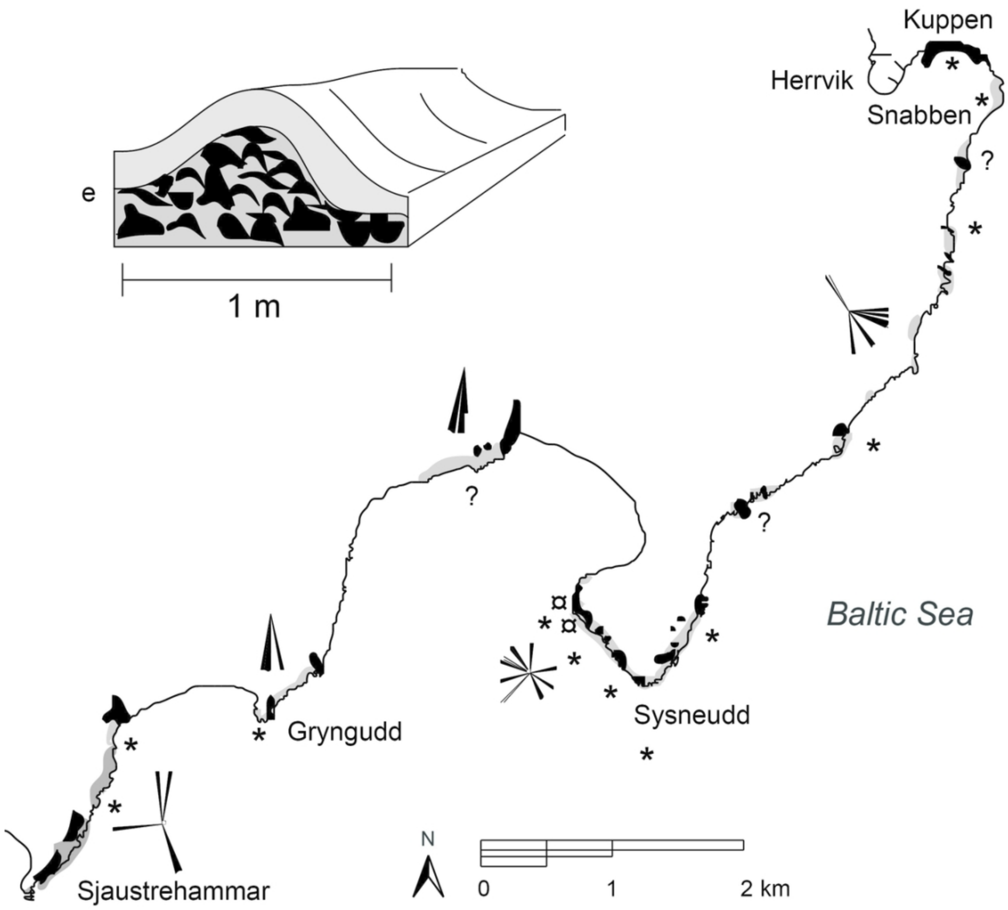

Figure 4. Map of the stretch from Kuppen to Sjaustrehammar, revealing the observed features of the Kuppen-Snabben Unconformity Complex and associated facies. Black = reef facies; gray = conglomerates; * = association (as described by the inset figure); ? = uncertain association; ¤ = erosional potholes (Silurian karst weathering); rose diagrams refer to the orientation of the axes of ridges as exemplified by the inset. The typical features of the association are shown by the inset and described in the text. Photographs of the different association features are exemplified in Fig. 5.

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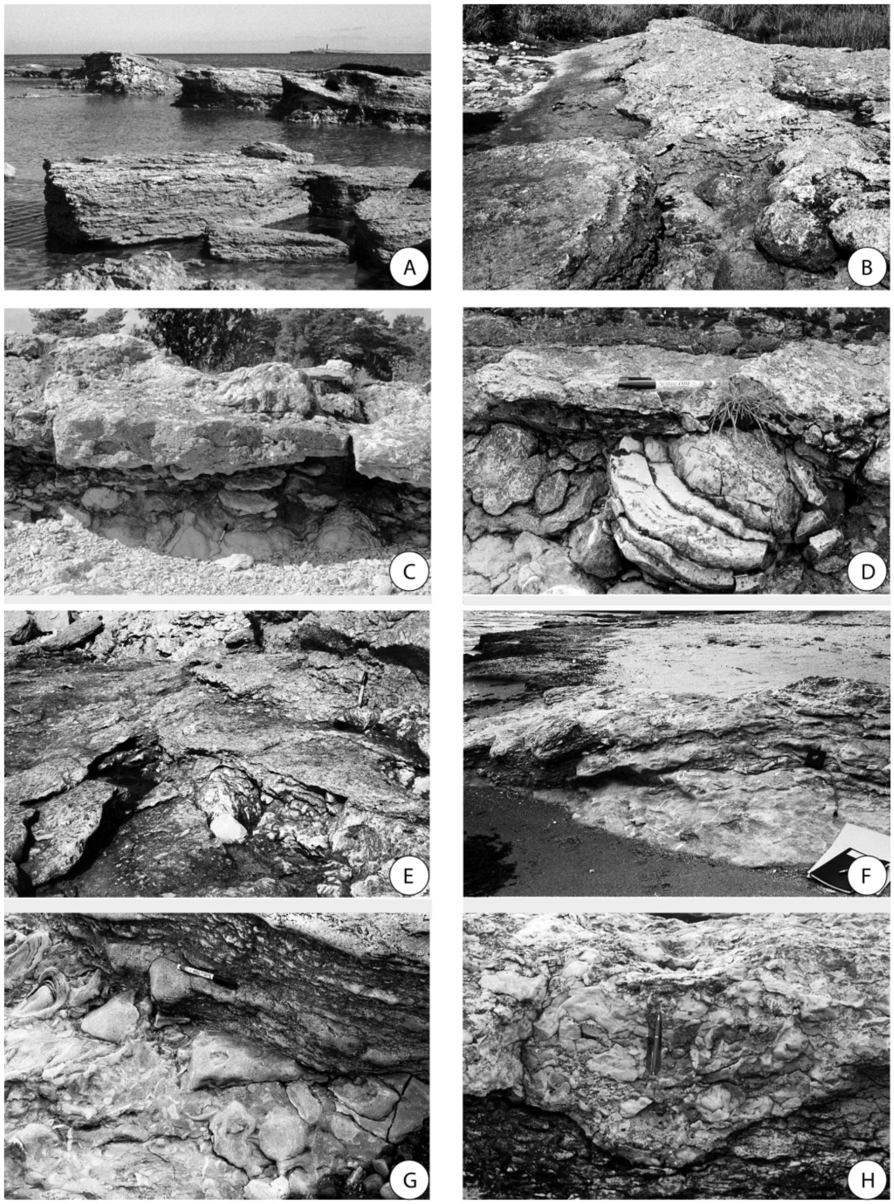

Figure 5. Examples of the Snabben unconformity association found between Kuppen and Sjaustrehammarn. A. Type area for the association at Snabben. B. Flank sediments draping a reef ridge (Gryngudd). C, D. Conglomerates cutting truncated stromatoporoids (along the stretch between Snabben and Sysneudd). E. Conglomeratic shales draping reef facies (along the stretch between Sysneudd and Gryngudd) F. Conglomerates (left) intercalating with reef facies (right; close to Sjaustrehammar). G. Conglomeratic shales on truncated stromatoporoids (reef facies; Sysneudd). H. Potholes (karst) filled with stromatoporoid floatstones (Sysneudd).

170x230mm (300 x 300 DPI)

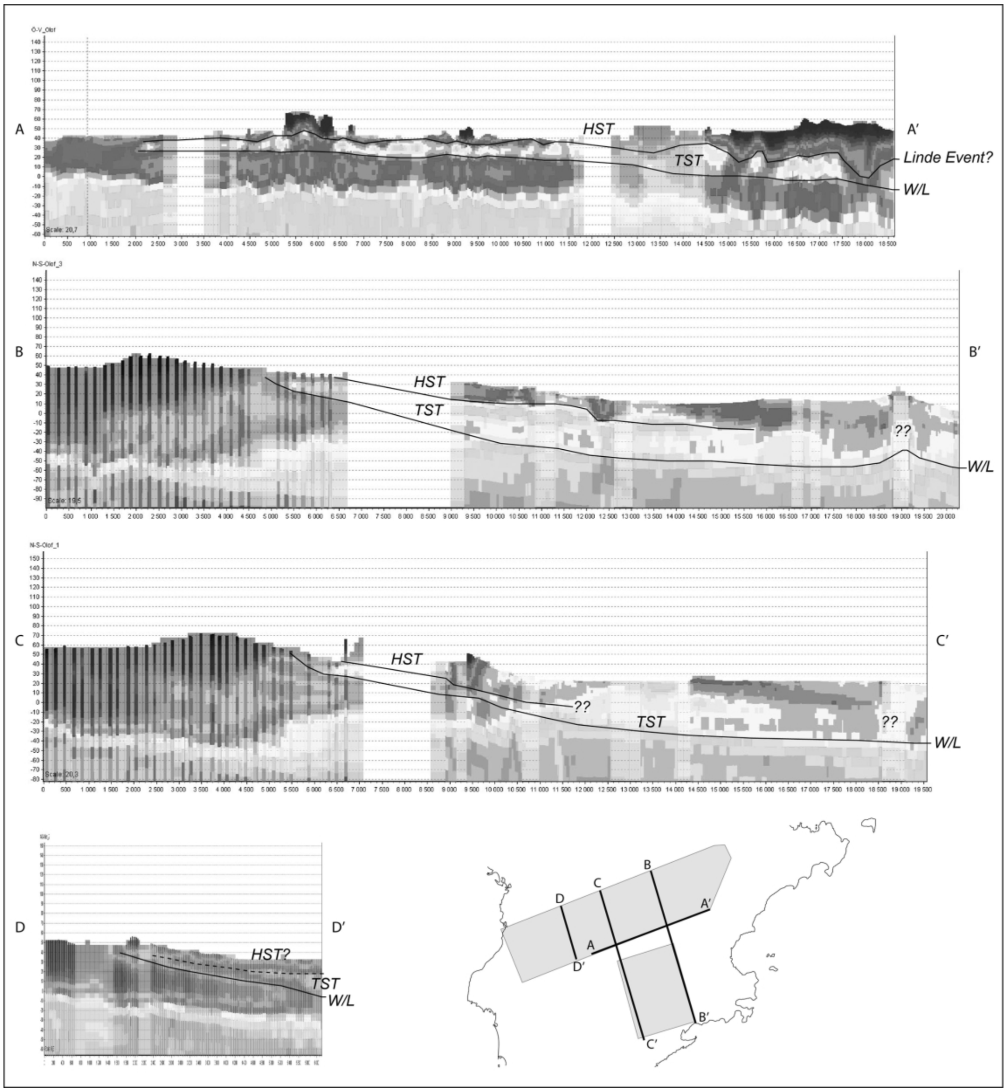

Figure 6. ATEM profiles across the Hemse Gp outcrop area with the Wenlock-Ludlow boundary (W/L) indicated as well as the overlying strata, herein interpreted as belonging to the transgressive (TST) and highstand (HST) systems tracts. The boundary between the two systems tracts, i.e. the maximum flooding surface (MFS) marks the approximate position for the Linde Primo-Secundo Event. ?? = Uncertain. Lower right map inset shows the area where ATEM measurements were made during the years 2014-2015 (light gray) and the specific profiles used in this paper (black lines).

183x199mm (300 x 300 DPI)

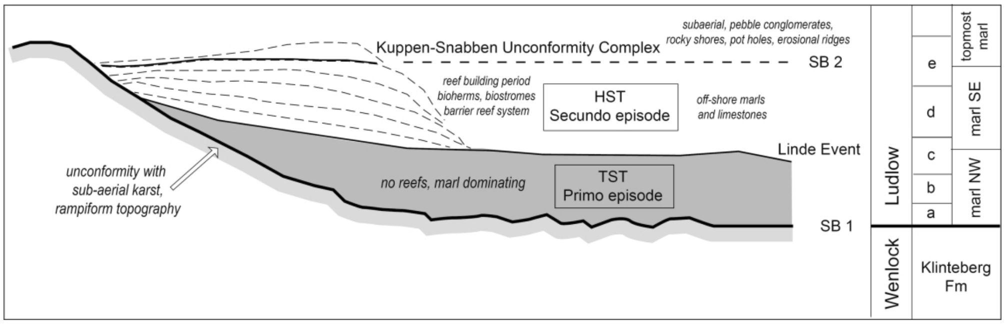

Figure 7. Diagram of the interpreted sequence for the Hemse Group reef development.

225x71mm (300 x 300 DPI)