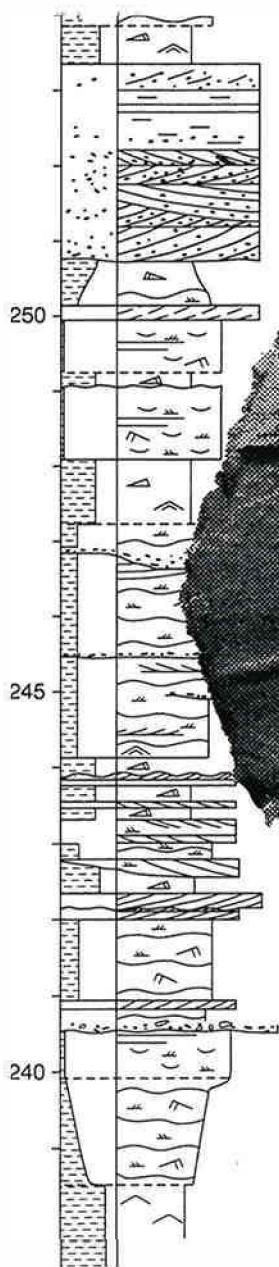


Depositional evolution of a reef-dominated Upper Permian carbonate platform, Wegener Halvø Formation, Karstryggen area, East Greenland

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**Formation of Source and Reservoir Rocks in a Sequence Stratigraphic Framework,
Jameson Land, East Greenland
Havniveau-kontrolleret dannelse af Kilde- og Reservoirbjergarter**

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**DEPOSITIONAL EVOLUTION OF A REEF-DOMINATED UPPER PERMIAN
CARBONATE PLATFORM, WEGENER HALVØ FORMATION, KARSTRYGGEN
AREA, EAST GREENLAND**

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ABSTRACT

The Wegener Halvø Formation carbonate platform in the Karstryggen area consists of three third order depositional sequences that formed in response to three Kazanian sea level cycles. Pinning point curves for the subaerial exposure surfaces separating the depositional sequences quantify the amplitude of the relative sea level fluctuations in the range of 70-140 m. The Karstryggen platform developed on top of a karstified older Permian carbonate platform and pre-depositional relief was locally exceeding 70 m. The pre-depositional relief influenced deposition in all three sequences. Algal-cement buildups formed over karst pinnacles and merged during time to form a N-S trending barrier dissected by deep fluviially modified karst channels. Peritidal carbonates formed behind the barrier whereas off platform sedimentation was dominated by thin transgressive siliciclastics overlain by shallow marine algal-foraminifer grainstones in the first two sequences. During the last sea level cycle prograding oolitic grainstones formed basinwards of the algal-cement buildups.

Transgressive systems tracts are thin and often dominated by condensed siliciclastic units in off platform areas and palaeolows. Over palaeotopographic highs it consists of aggrading algal cementstones. Highstand deposits are limited to palaeotopographic elevated areas and consist of algal cementstones along the basin margin and shallow subtidal to intertidal carbonates and evaporites in the platform area. Outside these areas carbonate deposition took place during falling sea level, and during deposition of the first two sequences thin laterally extensive units of shallow marine grainstones were deposited directly on top of deeper marine siliciclastics. During the final sea level fall, thick prograding units of oolitic grainstones were deposited.

INTRODUCTION

The Upper Permian carbonates in central East Greenland was deposited at a palaeolatitude of approximately 32-35°N, close to the confluence of the equatorial and mid-latitude atmospheric circulation cells (Scotese and McKerrow, 1990; Scholle, Stemmerik et al., 1993). This climatic sensitive location is approximately midway between the areas of cool-water carbonate deposition in North Greenland and the Barents Sea and the warm and arid areas of the Zechstein basin in NW Europe (Figure 1; Stemmerik, 1995; Stemmerik, 1997). The East Greenland carbonates therefore provide important information for the general evolution of the region. More importantly, however, they form a link that allows correlation between these cool-water and warm-water carbonates and studies of, how the palaeogeographic setting influenced on their response to fluctuations in relative sea level. The climatic sensitivity is best documented during a late Permian sea level fall where a change from a semiarid to a humid climate led to extensive dissolution of evaporites and aragonite-dominated older Permian carbonates. This resulted in a rugged karstic palaeotopography beneath the Upper Permian Wegener Halvø Formation platform deposits. The karstic relief provides a unique possibility of estimating the minimum amplitude of eustatic sea level fluctuations during platform deposition by constructing a pinning point curve (Goldstein and Franseen, 1995; Stemmerik, in prep.).

Previous work in the area has mainly focused on the diagenesis and porosity evolution of these rock as they form the only onshore equivalent for Permian exploration in the North Atlantic, and only the gross facies patterns have been described (Surlyk, Hurst et al., 1986; Scholle, Stemmerik et al., 1990; Scholle, Stemmerik et al., 1991; Stemmerik, 1991; Scholle, Stemmerik et al., 1993; Stemmerik, Christiansen et al., 1993; Stemmerik, Scholle et al., 1993). This paper will

concentrate on the sequence stratigraphy and depositional facies of the Wegener Halvø Formation carbonate platform in the Karstryggen area along the western margin of the Late Permian depositional basin (Figs. 1, 2). The platform developed during three Kazanian sea level cycles that during lowstand led to subaerial exposure of the entire platform and the upper parts of the slope. Deposition was mainly aggradational during the first two sea level cycles and not until the latest sea level highstand was carbonate production able to outpace sea level and grainstones started to prograde basinwards and towards depositional lows in the platform area. The gross facies patterns and related diagenesis were described by Scholle, Stemmerik et al. (1993) and Stemmerik, Scholle et al. (1993) based on field work in the area. However, outcrops are generally hardly assessable and in order to improve the understanding of the platform and its correlation to the shale-dominated basinal succession, a shallow core programme was carried out in 1993 (Piasecki, Surlyk et al., 1994). A total of six shallow cores with a length of 56 m to 95 m was drilled using helicopter portable equipment developed at the former Geological Survey of Greenland. The cores were drilled in an east-west transect across the platform margin from a position approximately 750 m behind the proposed platform break to approximately 2100 m basinwards (Fig. 2). The drilling was supplemented with detailed facies mapping and where possible, cores were tied together in the field using distinctive subaerial exposure surfaces as marker beds. The new information arising from these cores and a more detailed facies mapping of the eastern platform margin calls for a revision of the depositional model proposed by Scholle, Stemmerik et al. (1993) and Stemmerik, Scholle et al. (1993). Most importantly, the platform margin is reef dominated, like the platforms along the eastern basin margin, and not grain-dominated as previously suggested. The majority of the grainstones was deposited during highstand and falling sea level of the latest of the Kazanian sea level cycles.

REGIONAL SETTING AND STRATIGRAPHICAL FRAMEWORK

In central East Greenland, post-Caledonian faulting and subsidence began during the Early Devonian within a regional transtensional tectonic framework (Larsen and Bengaard, 1991). The structural style changed during the latest Devonian, and during the Carboniferous block faulting was associated with east-west extension (Stemmerik, Vigran et al., 1991). Sedimentation during these early stages of basin evolution was non-marine and marine conditions were not established until the Late Permian when the sea transgressed an elongated approximately 400 km long and up to 80 km wide, north-south oriented depression (Surlyk, Hurst et al., 1986). The Late Permian depositional basin is bounded to the west by a major fault system, the post-Devonian Main Fault, that has controlled basin subsidence from the latest Devonian and onwards (Fig. 1). The basin most likely was landlocked towards the south and towards the southeast it is separated by the Liverpool Land High from the rift basins that formed the main sea way connecting the Zechstein Basin of Northwest Europe with the Permian basins in North Greenland and the Barents Sea (Fig. 1) (Stemmerik, 1995).

The Late Permian transgression followed Carboniferous syn-rift sedimentation in narrow rotated half-grabens and a prolonged period of uplift and erosion in the early Permian associated with a change from active rifting to more passive regional subsidence (Stemmerik, Christiansen et al., 1993). Differential subsidence still occurred across major lineaments and influenced sedimentation during the Late Permian (Stemmerik, Christiansen et al., 1993). The initial transgression resulted in deposition of a thin succession of fluvial to paralic conglomerates and red siltstones (Huledal Formation in Fig. 3). They pass into a thick succession of shallow marine

carbonates and evaporites dominated by micritic, peloidal and stromatolitic limestones and dolomite, and localised subaqueous gypsum (Karstryggen Formation in Fig. 3). Termination of Karstryggen Formation deposition was marked by a major drop in relative sea level and the carbonates and evaporites were subjected to a prolonged period of Late Permian subaerial exposure (Scholle, Stemmerik et al., 1993). Along the basin margins, considerable topographic relief, locally in excess of 100 m was produced by karstification and fluvial erosion during this hiatus.

The rugged karstic topography was transgressed during a second major Late Permian transgression that resulted in deposition of fully marine carbonates of the Wegener Halvø Formation along basin margins and over structural highs and black shales of the Ravnefjeld Formation in the central parts of the basin (Figs. 1, 3)(Surlyk, Hurst et al., 1986; Stemmerik, Christiansen et al., 1993; Stemmerik, Scholle et al., 1993). Conodonts from these formations gave a Kazanian age (Rasmussen, Piasecki et al., 1990) and within the present biostratigraphic resolution it is most likely that the Wegener Halvø and Ravnefjeld Formations correlate to the Zechstein-1 and -2 cycles in Northwestern Europe (Stemmerik, 1995). The Wegener Halvø and Ravnefjeld Formations corresponds to three third order depositional sequences (Piasecki and Stemmerik, 1991; Stemmerik, Surlyk et al., 1992; Christiansen, Piasecki et al., 1993). Each sequence is in the platform areas characterised by a general shallowing upwards facies trend and capped by subaerial exposure surfaces (Scholle, Stemmerik et al., 1991; Stemmerik, 1991; Scholle, Stemmerik et al., 1993; Stemmerik, Scholle et al., 1993) whereas they in the basinal areas are characterised of shift between laminated organic-rich shales and bioturbated organic-lean shales (Piasecki and Stemmerik, 1991; Stemmerik, Surlyk et al., 1992).

In the study area of Karstryggen along the southwestern margin of the basin, the Wegener Halvø Formation ranges in thickness from less than 30 m to more than 100 m being thinnest

towards the west. Scholle, Stemmerik et al. (1993) in their study documented that the facies distribution to a large degree is controlled by the relief of the underlying Karstryggen Formation surface and they distinguished four depositional regimes. Carbonate shoals and buildups were preferentially developed on palaeotopographic highs and during deposition they merged to form an elongated barrier defining the platform margin. Peritidal sediments dominate in the areas to the west where they locally pass into coarse-grained siliciclastics, resedimented carbonates and shales that were deposited in incised, fluvially modified karst valleys and/or karst sink holes. In the off platform areas to the east, deeper water subtidal carbonates dominate (Fig. 3).

The investigated cores represent three of these settings, only the peritidal platform succession has not been drilled. Core GGU 303133 represents the lower part of a palaeolow succession, cores GGU 303134 and 303137 are drilled through carbonate buildups sitting on palaeohighs whereas cores GGU 303135, 303136 and 303138 form a west to east transect from these buildups towards the basin (Fig. 4).

SEQUENCE CORRELATION

The biostratigraphic resolution does not allow proper identification of individual depositional sequences within the Wegener Halvø and Ravnefeld Formations. Correlation within the Karstryggen area is therefore based on tracing of the subaerial exposure surfaces defining the third order depositional sequences and is accordingly dependent on proper identification of these surfaces. This is relatively easy in the peritidal platform succession but causes troubles when approaching succession deposited in karstic palaeovalleys and over palaeotopographic highs, and the core data indicate that the correlation originally proposed by Scholle, Stemmerik et al. (1993)

and Stemmerik, Scholle et al. (1993) is wrong in these areas. Three units, each corresponding to a third order depositional sequence have been identified and correlated from the platform areas across the platform margin and into the off platform areas (Fig. 4).

Sequence boundaries

The SB 1 sequence boundary separating the Wegener Halvø Formation from the underlying Karstryggen Formation is a karstic surface that shows up to 72 m of topographic relief in the cross section from GGU 303133 to 303136 (Fig. 4). In map view this surface is highly irregular with several isolated karst sink holes, Stemmerik, Scholle et al. (1993) mapped several fluvial drainage systems incised into the Karstryggen Formation and Scholle, Stemmerik et al. (1993) suggested a linear palaeotopographic ridge towards the east (Fig. 2).

The top of the Karstryggen Formation consists of an up to 10 m thick zone of brecciated carbonates where siliciclastic material in form of reddish weathering clay, silt and sand occur as fracture- and cave fill. The cave-fill is occasionally laminated and contains angular to subrounded carbonate clasts varying in size from less than 1 cm to more than 5 cm. The primary textures of the carbonates are completely obliterated and they now consist of coarsely crystalline calcite. The precise position of the sequence boundary is often difficult to define due to the intense alterations. In GGU 303133 the boundary is placed at 49.3 m at the top of a breccie zone but below a conglomerate and in GGU 303136 it is placed at 48.7 m above an approximately 6 m thick weathered zone (Fig. 5).

The subaerial exposure surface defining SB 2 is less pronounced than the top Karstryggen Formation surface. In GGU 303134 it is picked at the uppermost of four exposure surface seen in the interval from 77.5 m to 84.6 m. It is an approximately 1 m thick exposure horizon consisting of

brecciated limestone with sand-filled fractures. In GGU 303133 it is also an approximately 1 m thick brecciated zone forming the top of a thick grainstone unit. There, fitted fabrics are common in the brecciated level and siliciclastic material is much more common than in GGU 303134. It occurs both in up to 1 cm wide fractures and as laminated cave fill of medium- and fine-grained sandstone. The exposure surface is overlain by a 25 cm thick transgressive layer of silt and fine-grained sandstone that partly fills the fractures.

SB 3 is a subaerial exposure surface where the carbonates are brecciated and red-stained in GGU 303133. The uppermost 10 cm of this zone consists of angular to subangular limestone fragments encased in red clay. Below, up to 1 cm wide fractures filled with red clay and medium- to fine-grained sand are common. It is developed in shallow intertidal to supratidal carbonates forming the top of a peritidal shallowing upward succession. The sequence boundary is similarly developed in GGU 303135 and 303136. In GGU 303134, this surface consists of 65 cm brecciated limestone with 1-2 cm wide, clay-filled fractures that downwards expand to small hollows where the carbonate surface is micro-karstic with 2-3 cm of relief. Following a relatively undisturbed zone, heavily dissolved limestones with cave-fill of coarse-grained sand and limestone clasts extend down to 3 m below the surface.

The SB 2 and SB 3 surfaces show almost as much relief as the SB 1 surface. In the cross section from GGU 303133 to 303136, only minor modifications are seen as a consequence of deposition during the first two Wegener Halvø cycles (Fig. 4). The variations in palaeoaltitude mean some areas have been subjected to much longer and possibly more frequent subaerial exposure and this may explain the lateral variations seen along the sequence boundaries. Generally speaking, the most well developed SB 2 and SB 3 exposure surfaces are seen over palaeotopographic highs where the sediments are expected have been exposed for the longest periods of time.

Correlation

The SB 1 sequence boundary defining the base of the Wegener Halvø 1 Sequence has been identified in cores GGU 303133 and 303136 and field observations show that it is located approximately 15-20 m below the bottom of GGU 303134 and 40-45 m below the base of GGU 303135 (Figs 4, 5). The SB 2 sequence boundary defining the top of the this sequence has been identified in GGU 303133, 303134, 303136 and 303137 and within the study area the thickness of the Wegener Halvø 1 Sequence ranges from 13-40 m (Figs 4, 5). The SB 3 sequence boundary defining the top of the Wegener Halvø 2 Sequence has been identified in GGU 303133-303137. This sequence ranges in thickness from 5-30 m (Figs 4, 5). The present day surface defines the top of the Wegener Halvø 3 Sequence in the Karstryggen area and therefore only minimum thicknesses can be given for this sequence. It ranges from approximately 20 m in platform locations near the site of GGU 303133 to more than 100 m at the site of GGU 303138 (Fig. 4); this variation appears largely to be related to recent erosion.

The SB 1 sequence boundary has 72 m of relief within the transect from GGU 303133 to 303136. This relief was only gradually reduced during deposition of the Wegener Halvø 1 and -2 Sequences and the SB 3 sequence boundary has 50 m of relief from platform margin to the intraplatform depression near GGU 303133 (Fig. 4). This relief was reduced considerably during Wegener Halvø 3 times but present day erosion prevents a precise estimate.

SEDIMENTARY FACIES

Wegener Halvø 1 Sequence

Five depositional facies have been distinguished in the Wegener Halvø 1 Sequence. The carbonates in the lower part of the sequence are often completely altered and their primary fabrics are not preserved.

Marine shales

Marine shales have been found both in cores GGU 303133 and 303136. In GGU 303133, approximately 5 m of black, laminated organic-rich shale with thin, 5-15 cm, layers of massive carbonate mudstone occur. The total organic content (TOC) of these shales ranges from 1.74% to 4.56% (average ca 2%) and the HI index ranges from 49 to 115 (average ca. 100). The highest organic content is found at the base of the unit, in shales with the lowest HI index, suggesting dominance of terrestrially derived organic material. The laminated shales pass upwards into non-laminated grey, organic-lean shales. In GGU 303136, the shales are less than 1 m thick. They are non-laminated grey and organic-lean with rare brachiopods, and along the base of the thickest unit common gravel-size carbonate grains.

The laminated shales in GGU 303133 resemble the laminated facies of the Ravnefjeld Formation (e.g. Piasecki and Stemmerik, 1991), and it is suggested that they were deposited in similar environments, i.e. deep water and anoxic bottom conditions (Christiansen, Piasecki et al., 1993). However, so far laminated shales have not been reported from this stratigraphic level in the exposed parts of the basin. There, the Wegener Halvø 1 Sequence consists of shallow marine carbonates or bioturbated siltstones (Piasecki and Stemmerik, 1991; Christiansen, Piasecki et al.,

1993). The non-laminated facies in GGU 303133 and 303136 was deposited in more well oxygenated water, and it is suggested to represent shallower depositional conditions like those recognised in marginal basinal settings (e.g. Piasecki and Stemmerik, 1991). The carbonate grains incorporated in this facies in GGU 303136 are reworked from the underlying carbonates during transgression.

Red siltstones

Red and occasionally greenish weathering organic-lean siltstones form from less than 10 cm to more than 1.5 m thick beds in the lower part of the sequence. These siltstones are massive and material similar to these siltstones often fills fractures in the underlying carbonates.

There is no evidence of subaerial exposure associated with these siltstones and rather than defining soils they are suggested to have formed subaqueously by reworking of soil material from exposed palaeotopographic highs down into the submerged palaeolows during sea level lowstand and early transgression.

Micritised grain - algae grainstone

This facies consists of bedded, 10 cm to more than 150 cm, fine-grained grainstones dominated by fragments of algae, micritised grains and encrusting foraminifers. The micritised grains are subrounded to angular, massive or occasionally they consist of a leached core surrounded of a thin micritic envelope. The grains are usually less than 0.5 mm but occasionally they are cemented together to up to 10 mm large lumps. They occur together with rare to abundant fragments of algae and ostracods and locally common encrusting foraminifers. The cement is clotted peloidal to finely crystalline.

This facies represents deposition in a shallow marine environment with increased salinity or otherwise biological stressed conditions. The pervasive micritisation of grains indicates deposition in water depth of only a few metres. The absence of ooids suggests a somewhat protected environment. The shallow marine setting of this facies is supported by the common presence of solution breccias and other evidence of subaerial exposure at the top of this facies. In the Wegener Halvø 2 Sequence this facies is interbedded with algally laminated limestone supporting a very shallow, and biologically stressed depositional environment.

Intraclast conglomerates/breccias

This facies consists of up to 130 cm thick beds of intraclast conglomerates and/or *in situ* brecciated carbonates with common siliciclastic material in the matrix. It is rather difficult to distinguish between the *in situ* brecciated beds and the transported conglomerates but in all cases transport distances appear to be small. The intraclasts consist most commonly of homogenous, recrystallised calcite; fragments of micritised grain - algae grainstone are locally common.

This facies represents events of subaerial exposure, karstification and reworking of carbonates. The fragments are always sourced locally whereas the abundance of siliciclastic sand- and silt-size material suggests fluvial reworking of the more siliciclastic-rich conglomerates.

Algae grainstone/cementstone

The algae grainstone and cementstone facies is confined to GGU 303134 and 303137. It consists of encrusting algae and fragments of platy algae, rare to common bryozoans and rare brachiopods encrusted by early marine, radial fibrous cement. Cementation is pervasive and often this facies is a cementstone. It contains abundant brecciated horizons where fragments of this facies

are cemented by a new generation of marine cement. Occasionally, sand size siliciclastic material is associated with these breccias. This facies forms the basal parts of a linear several kilometres long, less than 500 m wide and more than 90 m thick algae-dominated buildup.

The algae cementstones are suggested to have formed in shallow, moderate to high energy settings. The presence of bryozoans and brachiopods indicates that the environment at least occasionally was normal marine. The repeated dissolution and brecciation seen in this facies suggest deposition close to sea level where even small fluctuations would led to exposure and dissolution of the marine cement.

Wegener Halvø 2 Sequence

The Wegener Halvø 2 Sequence does not include any marine shales in the study area. It is composed mostly of algae-dominated shallow marine carbonates. In addition to the facies described here, the Wegener Halvø 2 Sequence also includes micritised grain-algae grainstones like those described in the Wegener Halvø 1 Sequence. Shallow marine sandstones and very sand-rich carbonates occur immediately above the SB 2 sequence boundary and over other, less significant subaerial exposure surfaces.

Foraminifer-algae packstone/grainstone

The dominant grains are foraminifers, plates of algae and micritised grains. Additional grains include rare gastropods, ostracods and bivalves and in a few intervals bryozoans. The micritised grains are subrounded and usually less than 0.5 mm in diameter. Occasionally, only the outer rim is micritised and in these cases, the grains often are fragments of platy algae or bivalves. Most foraminifers are encrusting forms sitting on fossil fragments, *Agathammina pusilla* is rare in this

facies. The foraminifer and algae dominated facies both occur as packstones and grainstones, the grainstones being by far the volumetrically most important. The grainstones are cemented by clotted peloidal to finely crystalline cements like those seen in the micritised grain- algae grainstones. The cement seems in part to be early marine, as it often cements several micritised grains together to up to 2 mm, irregular lumps.

This facies represents deposition in a protected shallow marine environment. The predominance of foraminifers and platy algae indicate warm, normal marine conditions and the widespread micritisation of grains indicates deposition in shallow water, well within the photic zone. This facies is suggested to represent a slightly deeper and biologically less stressed environment than the micritised grain-algae grainstones.

Algally laminated limestone

The algally laminated limestones form up to 1.5 m thick beds of carbonate mudstone with undulating lamination. Most commonly, it forms less than 0.5 m thick beds that are cyclically interbedded with micritised grain-algae grainstones.

Algally laminated limestones usually form in protected intertidal to shallow subtidal settings. The lack of evaporite nodules and gypsum crystals in this facies suggests that it most likely formed in shallow subtidal, biologically stressed settings.

Algae cementstone

The algae cementstone facies forms a massive to poorly bedded, 18-20 m thick unit in GGU 303134 and 303137. It resembles the algae grainstone/cementstone facies of the Wegener Halvø 1 Sequence. It is however more cement-rich and often completely dominated by marine cement.

Algae remains are the dominant grains in this facies but in the lower part fragments of bryozoans occur frequently. Brecciation and recementation of clasts is less common in this facies than in the algae grainstone/cementstone facies in the Wegener Halvø 1 Sequence.

The algal cementstones form the core of lenticular carbonate buildup that stack on top of the Wegener Halvø 1 algae buildups. This facies apparently formed in shallow high energy environments where rapid marine cementation prevented removal of the sediment..

Bioturbated silty packstone

This facies consists of biogenic packstones with up to 5% silt-sized quartz grains and small mm- to cm- size intraclasts. The fauna is dominated by bivalved ostracods, thin-shelled bivalves and foraminifers like *Nodosaria permiana*. Fragments of bryozoans and brachiopods are rare. The sediment is intensely bioturbated with no identified trace fossils.

The bioturbated silty packstone directly overlies a subaerial exposure surface. The intraclasts are reworked material from this surface. The fauna suggests normal marine, quiet depositional conditions well below wave base.

Wegener Halvø 3 Sequence

The Wegener Halvø 3 Sequence includes 7 distinctive depositional facies of which only the algal cementstone and micritised grain-algae grainstone facies are in common with those recognised in the previous sequences.

Packstone

This facies consists of fine-grained packstones where the most important grains are subrounded to angular and consist of a thin micritic envelope surrounding a leached, now cement-filled core. Occasionally, the shape indicates that grains are fragments of bivalves or algae. The grains are usually less than 0.2 mm, in rare cases they are up to 1 mm. They occur together with rare fragments of bryozoans and bivalves and more common, although still rare foraminifers, including *Agathammina pusilla*, *Nodosaria permiana* and various encrusting forms. The matrix is clotted and occasionally finely crystalline calcite cement occur between grains.

This facies was deposited in a protected, shallow marine environment. Based on the grain content it is suggested to represent a setting between the micritised grain-algae grainstone and the foraminifer-algae packstone/grainstone facies.

Oolitic grainstone

The oolitic grainstones are well bedded, 5-10 cm thick with highly variable grain content and size of the ooids. The ooids show a bimodal size distribution where the small grains range from 0.2-0.4 mm and the large from 0.8-1.5 mm. Fine-grained grainstones are confined to the lower part of the sequence whereas grainstones containing both large and small ooids becomes increasingly common towards the top. The small grains are usually poorly developed ooids with a thin rim showing concentric fabric and a relatively large core. The larger ooids have more well developed concentric fabric. The cores consist of leached material that is partly replaced by finely crystalline calcite, sand sized quartz grains or rarely bivalves, bryozoans and brachiopod fragments. Associated fauna elements include rare bryozoans, brachiopods, gastropods and foraminifers, particularly *Agathammina pusilla*, and more commonly bivalves. Biogenic grains are most common in the fine-

grained lower part. The grains are cemented by finely crystalline equant calcite, usually less than 0.05 mm. Large pores may contain up to 0.1 mm crystals. Fibrous cement is very rare; it forms less than 0.06 mm rims on some grains.

The ooids were formed in shallow moderate to high energy environment. The poorly developed concentric fabric on most grains suggest that they have spent relatively short time in this setting before they were transported into deeper, less agitated environments and most likely deposition took place below wave base. This is supported by the lack of primary current structures in this facies in contrast to most examples recorded from the literature (e.g.), and by field observations that indicate deposition in water depths exceeding 40 m. The overall coarsening upward trend and the abundance of ooids with leached core suggest deposition in gradually more shallow marine settings followed by post-depositional exposure and meteoric diagenesis.

Sandy biogenic packstone

The sandy biogenic packstone consists of 1-2 mm or smaller fragments of brachiopods, bryozoans, ostracods and bivalves, and foraminifers like *Agathammina pusilla*, *Nodosaria permiana*, *Geinitzina acuta*, *Calcitornella* sp. and various encrusting forms, together with large amounts of unidentified, often leached grains with micritic envelopes. Angular to subrounded quartz grains in the finest sand fraction, usually between 0.1 mm and 0.2 mm, constitute 10-20%, rarely 50% of the sediment and in some cases pure sandstone laminae occur.

The fauna indicate normal marine conditions and the presence of large amounts of micritised grains points towards a relatively shallow marine environment. The fragmentation of grains suggest moderate energy and the large amounts of sand point towards a nearshore environment. This facies follows immediately above a subaerial exposure surface and most quartz grains probably represent

reworked fluvial or aeolian material. Packstones with a similar grain composition and larger brachiopods but without quartz grains may represent a slightly deeper marine environment.

Bryozoan cementstone/grainstone

This facies consists of more than 30 m of massive to poorly bedded bryozoan-dominated grainstones and cementstones with rare levels of packstone. The fauna is completely dominated by bryozoans. Brachiopods and gastropods are rare whereas foraminifers and algae are more frequent. The fossils are cemented by early marine radial calcite cement or in rare cases clotted peloidal cement.

This facies resembles bryozoan-dominated facies from buildups along the eastern basin margin (Scholle, Stemmerik et al., 1991; Stemmerik, 1991). It represents a +30 m thick, 300 m wide and 1 km long isolated mound.

Open marine packstone/wackestone

The open marine packstone differs from all previously described facies by having a more diverse fauna of bryozoans, brachiopods, foraminifers and bivalves. Algae are also present as are micritised grains. This facies is thinly bedded and graded bedding is commonly seen. Occasionally thicker, stacked fining upward cycles of packstone and wackestone occur.

This facies resembles the distal flank deposits surrounding the bryozoan buildups on Wegener Halvø along the eastern basin margin (Scholle, Stemmerik et al., 1991; Stemmerik, 1991). The main difference is the complete absence of crinoids or other echinoderms in the Karstryggen deposits. By comparison to the Wegener Halvø area this facies is suggested to represent an open marine setting where the main sediment source was an adjacent carbonate buildups.

PLATFORM EVOLUTION

Wegener Halvø 1 time

The Wegener Halvø 1 Sequence ranges in thickness from approximately 13 m in the off platform areas represented by GGU 303136 to 32 m in an intraplatform palaeolow represented by GGU 303133. The platform margin algal-cement reef complex is 30-35 m thick at the site of GGU 303134 where only the upper 16 m have been cored. The lower sequence boundary corresponds to the top of the Karstryggen Formation and, as previously described, it is a mature karst surface. This surface shows considerably relief and lies c. 70 m higher in GGU 303134 than in GGU 303133 (Fig. 4).

This pre-depositional relief greatly influenced sedimentation. Deposition started during late lowstand or early transgression in the intraplatform lows with deposition of stacked fluvial intraclast conglomerates and shallow marine limestones that became subaerially exposed and brecciated. As sea level proceeded to rise, siliciclastic material became more fine-grained and the shallow marine carbonate grainstones now became interbedded with red silt size material that was washed from the surrounding, still exposed palaeohighs into the shallow basin. During the late lowstand and early transgression, the sea only reached the deeply eroded palaeolows and sedimentation was limited to these areas (Fig. 6). Not until the latest parts of the sea level rise was the entire area flooded, and the platform became established. This event is recorded by thin transgressive shales with reworked limestone grains in GGU 303136 and by a sudden change from red siltstones to black laminated shales in GGU 303133. The late transgressive to early highstand is characterised by deposition of organic-rich black shales in the intraplatform lows and thin bioturbated siltstones in the off platform area of GGU 303136. Carbonate sedimentation started over

palaeotopographic highs during this stage as recorded by the thin carbonate turbidites in the laminated shales. During maximum flooding and sea level highstand, small algal-cement buildups formed over the highest karst pinnacles and a linear algal reef barrier, that later connected the sites of cores GGU 303134 and 303137, started to form although at this early stage it most likely consisted of several isolated buildups (Fig. 6). Sea level was very shallow in these areas and repeated events of exposure and dissolution took place during the growth of the buildups.

At sea level highstand, the platform was thus divided by a N-S trending zone of high energy algal buildups into a western area of mainly peritidal carbonates and an easterly area of deeper marine, off platform sediments. The peritidal platform and the algal buildup belt was dissected by deep channels where marine sediments were deposited in maximum water depths exceeding 70 m (Fig. 4). There is no evidence of large scale facies progradation during sea level highstand. The shales in the palaeolows and the off platform areas, deposited at water depths of 30-70 m, are thus directly overlain by shallow marine carbonates. These carbonates form the forced regressive systems tract of the Wegener Halvø 1 Sequence. They consist of micritised grain-algae grainstones and rare interbeds of algally laminated limestone suggesting protected, biologically stressed depositional conditions.

The entire sequence thus shows relatively small thickness variations but large facies variations across the predepositional topography. The lack of highstand progradation may indicate that the carbonate production was somehow limited and evidently it was not large enough to significantly modifying the predepositional relief., and deposition has only very minor influence on the topography prior to deposition of the Wegener Halvø 2 Sequence (Fig. 6).

Wegener Halvø 2 time

The Wegener Halvø 2 Sequence ranges in thickness from c. 12 m in the intraplatform palaeolow at GGU 303133 to 20 m in the off platform areas of GGU 303136. The platform margin algal-cement reef complex is 18-20 m thick. The lower sequence boundary is, as previously described, a well developed subaerial exposure surface with considerably relief, up to 75 m within the studied section (Fig. 4).

The pre-depositional relief also controlled sedimentation during Wegener Halvø 2 time. The transgression is marked by reworking and deposition of red siltstones and fine-grained sandstones in the palaeolow and deposition of shallow marine grainstones in the off platform areas. Sedimentation was not able to keep up with rising sea level in these areas and the transgressive systems tract is very thin, 1-1.5 m, in the palaeolows (Figs 5, 6). In the off platform area, the grainstones pass upwards into marine packstone and finally into a thin siltstone that is suggested to represent the maximum flooding. This siltstone possibly correlates with the silty packstones at the base of GGU 303135. Over the palaeotopographic highs carbonate deposition first started during the later stages of the transgression when the growth of algal-cement buildups were re-established. The linear algal reef barrier started to be prominent at this stage although it still consisted of several isolated buildups.

At sea level highstand, the platform looked similar to the Wegener Halvø 1 platform. The high energy algal buildups divided it into a western area of mainly peritidal carbonates and an easterly area of deeper marine, off platform sediments. The peritidal platform and the algal buildup belt was dissected by deep channels where marine siliciclastics were deposited at maximum water depths exceeding 75 m (Fig. 4).

Again, carbonate production appears to be somehow limited and not large enough to allow large scale carbonate progradation and modification of the predepositional relief during sea level highstand. The siltstones in the palaeolows and the off platform areas, deposited at water depths of 30-75 m, are thus directly overlain by shallow marine carbonates of the forced regressive systems tract. They consist of algally laminated limestone interbedded with micritised grain-algae grainstones in GGU 303133. This suggests limited water exchange in the narrow channels during low sea level and biologically stressed conditions. In the off platform areas normal marine foraminifer-algae grainstones were deposited during this stage of platform evolution.

The Wegener Halvø 2 Sequence resembles the Wegener Halvø 1 Sequence both in showing limited lateral thickness variations and pronounced facies variations controlled by the underlying slightly modified karst topography.

Wegener Halvø 3 time

The final stages of development eventually changed the platform topography significantly and by latest Wegener Halvø 3 time the platform was grain dominated with linear shoals located adjacent to the algal barrier. The Wegener Halvø 3 transgression led to deposition of algal dominated grainstone facies in the nearshore areas and more mud-rich open marine facies in the distant off platform areas. These facies migrated towards the topographic highs as the sea level rise continued and at some stage during transgression carbonate deposition was limited to the topographically highest areas along the algal reef trend. There aggradational to slightly progradational parasequences of algal cementstone and grainstone formed narrow, up to 60 m high buildups. Later, possibly as the sea level rise slowed down, the depositional pattern changed and the former reef crest were replaced by a narrow oolitic grainstone shoal (Figs 5, 6). The lack of

accommodation space over the reef crest led to resedimentation of ooids both seaward and landward of the this shoal and thick grainstone wedges were deposited in these areas (Fig. 7). However, at this time the reef crest on which the oolite shoals formed stood at least 50 m over the adjacent sea-floor and grain production was not able to fill this space. Therefore, large scale progradation of the grainstones did not start until an eustatic fall in sea level forced grain production seawards and downwards. The youngest grainstone wedges thus from a forced regressive systems tract (Figs 5, 6).

At some stage during this sea level cycle small bryozoan buildups started to form in a localised area to the northeast, and during sea level highstand they merged to form up to 1 km long, 300 m wide and +30 m thick bryozoan buildups (Figs 2, 5, 6). These buildups are located basinwards of the easternmost outcrops of the prograding grainstone wedges and it is not possible to outline the precise stratigraphic relationship between these two facies belts.

DISCUSSION

The sequence stratigraphic interpretations outlined in the previous sections indicate that the evolution of the Karstryggen platform took place as the depositional response to three third order sea level cycles. The construction of a simple pinning point curve for the sediments using the method of (Franseen, Goldstein et al., 1993; Goldstein and Franseen, 1995) gives some quantitative constrains on the amplitude of the relative sea level fluctuations (Fig. 8). During construction of the curve all measured altitudes have been adjusted using the regional dip (5°ESE) given by (Larsen, 1987). The differences in elevation of SB 1 indicates a drop in relative sea level of at least 72 m to explain the observed karstic topography (Fig. 4). The starting point of the curve corresponds to the

lowest observed position of SB 1, 590 m in GGU 303133 (pinning point #1). The relative rise in sea level during deposition of the Wegener Halvø 1 Sequence was at least 107 m, from the lowest position of SB 1 to the highest position of SB 2 (pinning point #2) (Fig. 8). The following sea level fall that led to downslope migration of SB 2 was at least 75 m, from pinning point #2 to the lowest recorded altitude of SB 2 (pinning point #3). The following rise in relative sea level that led to deposition of the Wegener Halvø 2 Sequence was at least 93 m, from pinning point #3 to the topmost position of SB 3 (pinning point #4) (Fig. 8). The distance from pinning point #4 to the lowest position of SB 3 (pinning point #5) indicates that the following relative sea level fall was at least 81 m. The relative sea level rise that resulted in deposition of the Wegener Halvø 3 Sequence was at least 141 m, from pinning point #5 to the topmost position of the SB 4 in GGU 303134 (pinning point #6). The final sea level fall that led to deposition of the forced regressive systems tract of this sequence was at least 95 m, from pinning point #6 to the level of shallow marine oolitic grainstones in GGU 303136 (pinning point #8) (Fig. 8). The controls on these high amplitude sea level fluctuations are discussed in details elsewhere but most likely they contain a pronounced glacioeustatic signal (Stemmerik, in prep).

The Wegener Halvø 1 and -2 sequences have many features in common, and both differ significantly from the final Wegener Halvø 3 Sequence. All three sequences differ in internal architecture and facies distribution from the patterns usually recognised in land attached carbonate platforms although the observed lowstand karstification and the backstepping, retrogradational stacking patterns in the transgressive systems tracts conform sequence stratigraphic models for carbonates (Sarg, 1988; Handford and Loucks, 1993). Most carbonate platforms include fairly thick, laterally extensive highstand systems tracts as the results of increased rates of carbonate production and progradation during sea level highstands (Schlager, 1991; Handford and Loucks, 1993). The

progradation rates of modern carbonate platforms are controlled by production and accumulation rates and therefore vary depending on such factors as water depth, energy, depositional processes and climate. The highest production rates are recorded in tropical settings. The western margin of the Great Bahama Bank has been prograding into water depths of more than 400 m with an average rate of 1.3 m/ 1000 years over the last 5.6 my. (Ginsburg, McNeil et al., 1991), ooid shoreface deposits are prograding at rates of 100 m/1000 years at West Caicos Islands (Lloyd, Perkins et al., 1987) and even higher progradation rates are recorded from the Persian Gulf tidal flats.

The presence of ooids and the dominance of algae and foraminifers together with abundant marine cement in the East Greenland Permian deposits all point towards deposition in warm water conditions comparable to modern settings like the Persian Gulf. The potential carbonate production and progradation rates of the Karstryggen platform are therefore expected to be comparable to the modern examples given above. Furthermore, the proposed time equivalent deposits in the Zechstein basin further to the south includes wide carbonate platforms that follow the widely recognised patterns of broad shallow shelves that are able to keep up with rising sea level and prograde during sea level highstand (Stemmerik and Frykman, 1989; Tucker, 1991). Also, in the time equivalent cool-water carbonate system of North Greenland production rates are high enough to allow pronounced highstand progradation (Stemmerik, 1997). It is therefore obvious that local, probably intra-basinal restrictions on carbonate production occurred during deposition of the Wegener Halvø 1 and -2 sequences in the Karstryggen area.

The most likely processes to have influenced production rates are, except for the water temperature, salinity, water depth and water circulation. The East Greenland Permian basin was a narrow, partly closed basin (Fig. 2), where it is likely that water circulation was restricted and raised salinity should be expected in the southeasternmost parts of the basin. This assumption is supported

by the low diversity fauna recorded in the Wegener Halvø 1 and -2 sequences in this area, and the general absence of crinoids or other echinoderm in the Karstryggen platform deposits. However, the time equivalent basinal succession does not contain evaporites so salinity never raised to levels comparable with those seen in the Zechstein basin (Stemmerik, 1995). The basinal shale succession shows evidence of anoxic conditions at the sea bottom during sea level highstand (Piasecki and Stemmerik, 1991; Christiansen, Piasecki et al., 1993). The presence of organic-rich shales in the intra-platform areas like the site of GGU 303133 and further to the south (Surlyk, Hurst et al., 1986; Christiansen, Piasecki et al., 1993) indicates that anoxic conditions also occurred in at least the deeper parts of the platform during sea level rise and early highstand.

Carbonate production on reflooded carbonate platforms has a lag time of several thousand years and are not able to keep up with rising sea level during the initial stages (Schlager, 1991). This explains the backstepping parasequences in the transgressive systems tract of most carbonate platforms (Sarg, 1988; Handford and Loucks, 1993). During rapid, high amplitude rises in relative sea level this will stop carbonate production over large areas and if the entire platform is brought out of the photic zone carbonate production will end and the platform is drowned (Schlager, 1981; Schlager, 1991). The documented large rises in relative sea level during deposition of the Wegener Halvø Formation (Fig. 8) were apparently so rapid that carbonate production stopped over large areas and only the highest karst pinnacles remained shallow enough to support carbonate production. The palaeogeographic position of the platform makes it likely that the salinity was raised in the surface water, and the presence of shales deposited in anoxic conditions within the platform suggests that oxic conditions only existed in the shallowest part of the water column.

The limited carbonate production during sea level highstands of the Wegener Halvø 1 and -2 sequences can possibly be explained by high rates of relative sea level rise that drowned most areas

and only left isolated palaeotopographic highs the shallow subtidal zone, combined with environmentally stressed conditions due to raised salinity and low oxygen.

The shift from the sheet-like, draping Wegener Halvø 1 and -2 sequences to the strongly progradational, topography modifying shape of the Wegener Halvø 3 sequence is also reported from the time equivalent Wegener Halvø Platform along the eastern basin margin (Stemmerik et al., 1993; Stemmerik & Scholle, in press). In both areas, the Wegener Halvø 3 Sequence records a shift towards more open marine conditions as indicated by the more diversified fauna and the presence of bryozoan buildups. The relative sea level rise that led to deposition of the Wegener Halvø 3 Sequence is in the order of 140 m, and significantly larger than the sea level rises of the two preceding cycles. This may suggest that the tectonic component of this sea level rise was larger and possibly led to changes in the basin configuration.

During the initial transgressive phases of the Wegener Halvø 3 Sequence the depositional system resembles that seen during the Wegener Halvø 1 and -2 sequences, and it is not until the late transgressive to early highstand stage that deposition changed in the shallow water areas. The algal-cementstone buildups are abruptly overlain by oolitic grainstones. This shift in depositinal facies was associated with increasing production rates and eventually the shallow water system started to prograde. The internal architecture of the prograding oolitic grainstone wedge indicates that the main part of it was deposited during falling sea level as opposed to the previously discussed highstand progradation of oolitic deposits both on modern and other Permian platforms (Lloyd, Perkins et al., 1987; Stemmerik and Frykman, 1989; Tucker, 1991).

SUMMARY AND CONCLUSIONS

The Wegener Halvø Formation consists of a variety of shallow marine algal--dominated facies in the Karstryggen area. Oolitic grainstones and bryozoan-dominated deposits are limited to the youngest of the three depositinal sequences that make up the formation. Organic-rich shales deposited in anoxic environments constitute a minor proportion of the succession.

The Wegener Halvø Formation platform grew on top of the karstified surface of an older Permian carbonate platform and the depositional evolution of the platform was greatly influenced by the topography of this surface. Shallow marine deposits accumulated over karst pinnacles and during platform history they merged to form an elongated barrier of algal-cement buildups.

The evolution of the Karstryggen platform took place during three Kazanian sea level cycles. The relative sea level fluctuations have been quantified using the pinning point method of (Franseen, Goldstein et al., 1993; Goldstein and Franseen, 1995). The initial sea level fall that led to karstification of the underlying carbonate platform was at least 72 m. The relative sea level rises of the following three cycles range from 93-141 m and the sea level falls from 79-95 m.

Carbonate production was restricted during deposition of the Wegener Halvø 1 and -2 sequences possibly due to increased salinity and low oxygen content, and not large enough to support large scale highstand progradation. Therefore deposition off carbonates was limited in the off-platform areas and mainly took place during falling sea level. During the third Wegener Halvø sea level cycle depositinal conditions changed in the latest stages of the sea level rise and more open marine conditions were established. The results were higher carbonate production rates and large scale progradation during latest highstand and falling sea level. This late event eliminated the

predepositional karst topography that have been only slightly modified during deposition of the first two sequences.

The presence of organic-rich shale with potential as hydrocarbon source rocks in platform areas suggests a wider distribution of source rocks in the basin than previously expected. This may be of importance for exploration in the areas offshore mid-Norway as it indicates that anoxic conditions could be expected not only in the basins but also over the deeper parts of the footwall blocks during high relative sea level.

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CAPTIONS TO FIGURES

Figure 1. Palaeogeographic reconstruction of the seaway between Greenland and Norway during Kazanian time. The facies distribution corresponds to periods of high sea level. Modified from Stemmerik (1995).

Figure 2. General outline of the Late Permian depositional basin in central East Greenland. Areas of Permian outcrop and locality names are also shown. The inset map shows the Karstryggen area with distribution of major facies belts and location of the studied cores.

Figure 3. Schematic cross section of the Permian basin fill showing major lithostratigraphic units. Modified from Surlyk, Hurst et al. (1986).

Figure 4. Cross section of the Wegener Halvø Formation carbonate platform at Karstryggen along the A-A' in Fig. 2. The relative position of the cores have been adjusted using the regional dip given by Larsen (1987). Cores 303137 and 303138 are projected into the cross section.

Figure 5. Sedimentological logs of cores GGU 303133-303138.

Figure 6. Depositional evolution of the Karstryggen platform during Wegener Halvø 1 to -3 time.

A) Wegener Halvø 1, lowstand; B) Wegener Halvø 1, maximum flooding; C) Wegener Halvø 1, falling sea level. The peritidal platform and the algal-cement buildups is exposed while sedimentation still occurred in the off platform area and in the palaeolows; D) Wegener Halvø

2, maximum flooding. Note situation is similar to the Wegener Halvø 1 maximum flooding; E) Wegener Halvø 2, falling sea level. Note intertidal deposition on the peritidal platform; F) Wegener Halvø 3, early highstand. Note the shape of the Wegener Halvø 1 and -2 sequences and the more open marine off platform facies of the Wegener Halvø 3 sequence; G) Wegener Halvø 3, falling sea level. Note both landward and seaward progradation of oolitic grainstones.

Figure 7. The drill site of cores GGU 303134 and 303135 showing the massive core of the algal-cement buildups, the steeply dipping resedimented oolitic grainstones of the late highstand systems tract and the more gently dipping forced regressive systems tract of the Wegener Halvø Sequence 3.

Figure 8. Pinning point relative sea level curve for the Wegener Halvø 1-3 sequences in the transect A-A' in figure 2.

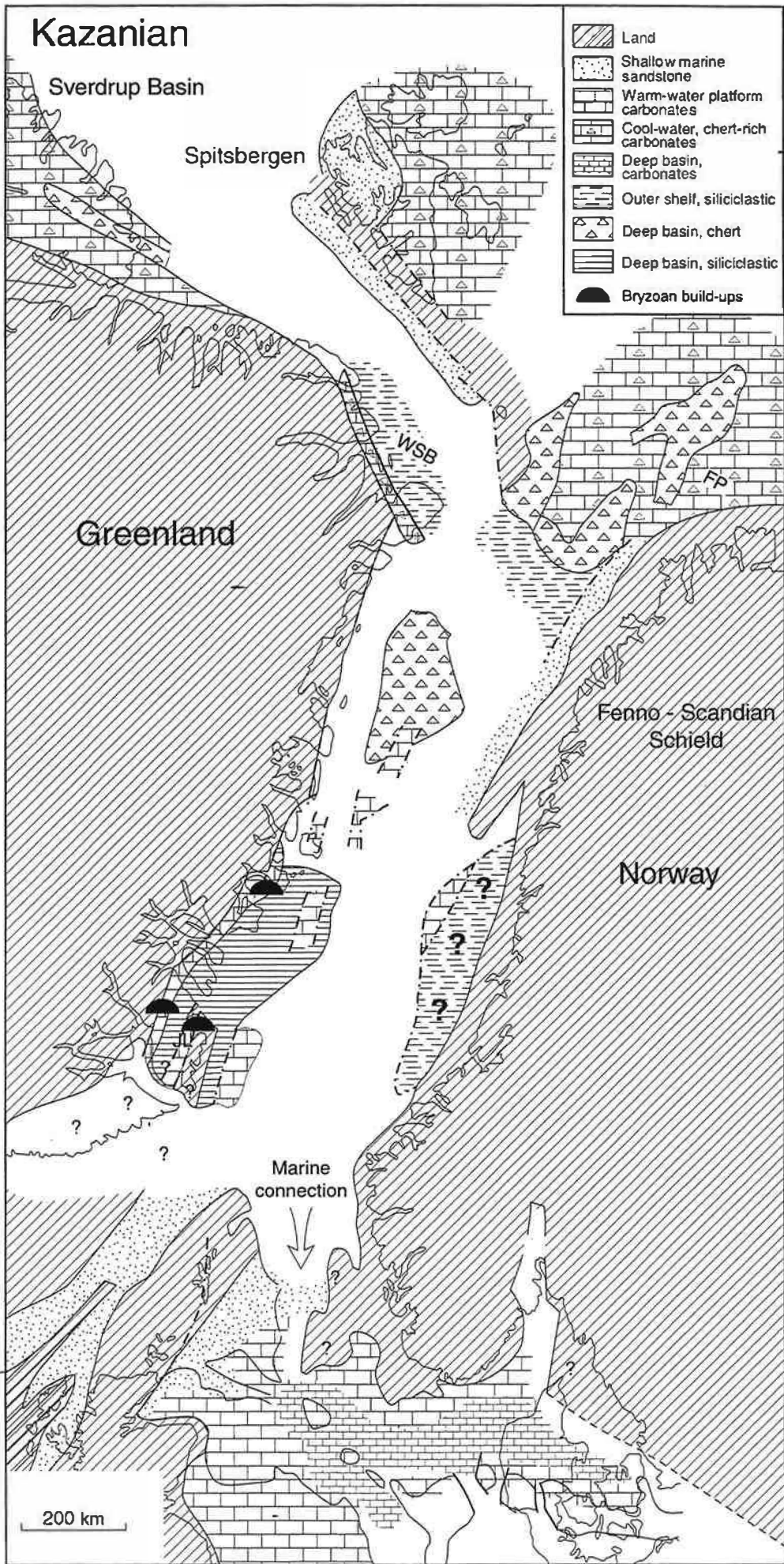


Fig. 1

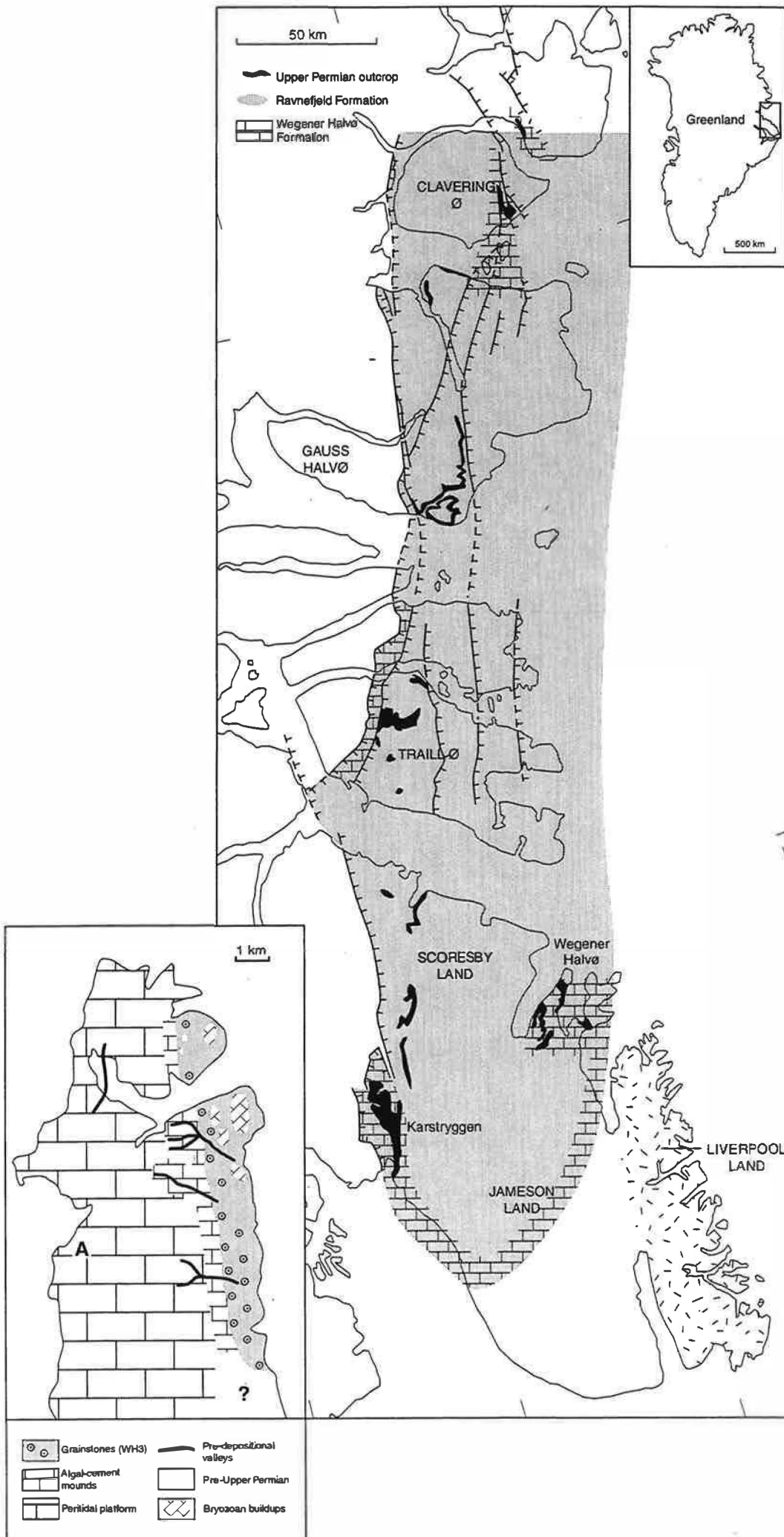


Fig. 2

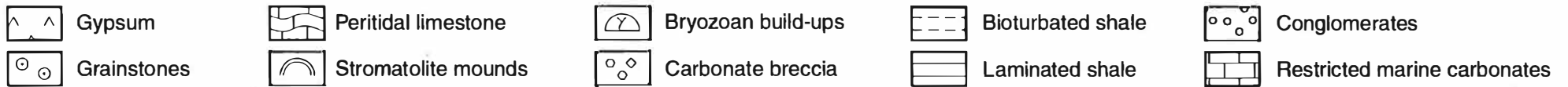
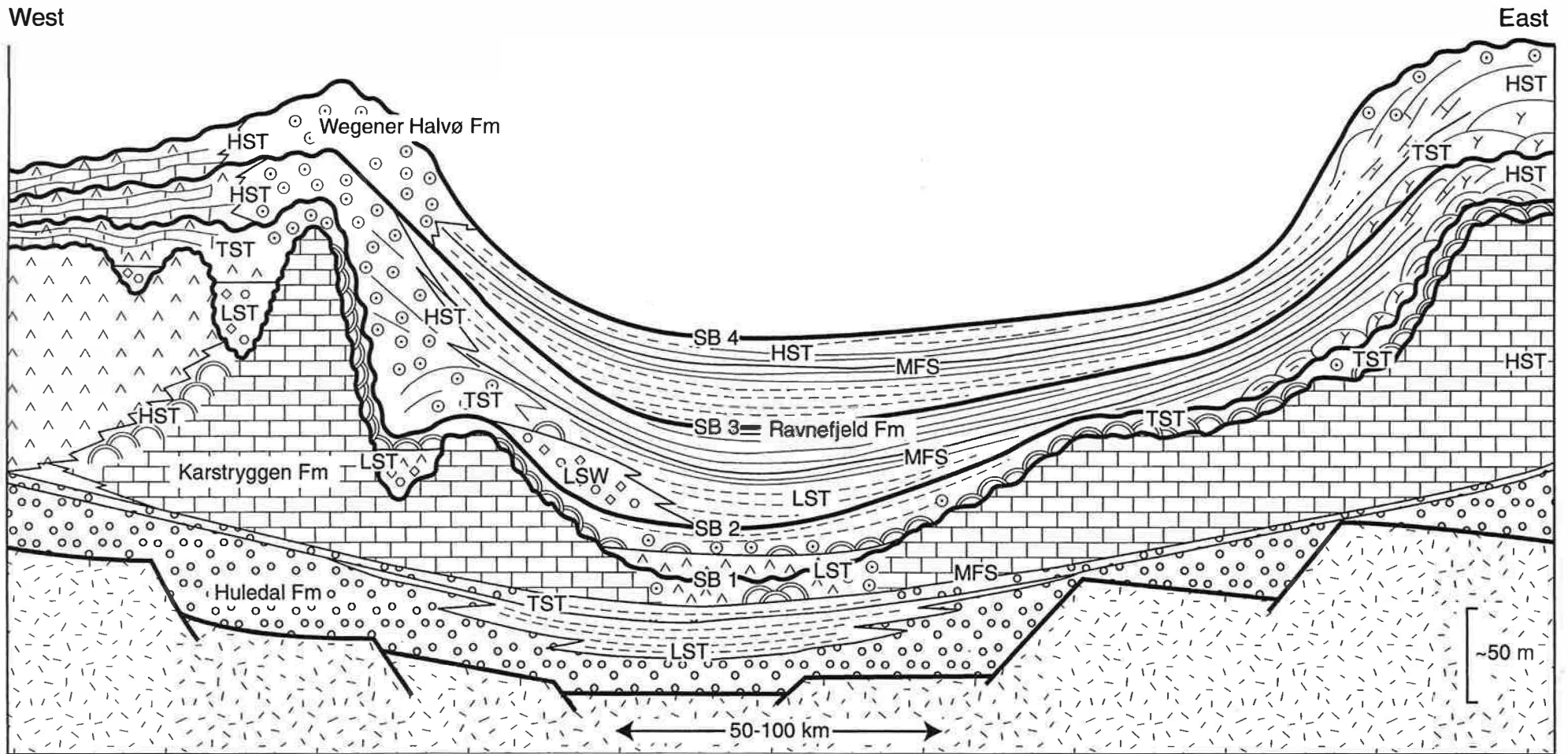


Fig. 3

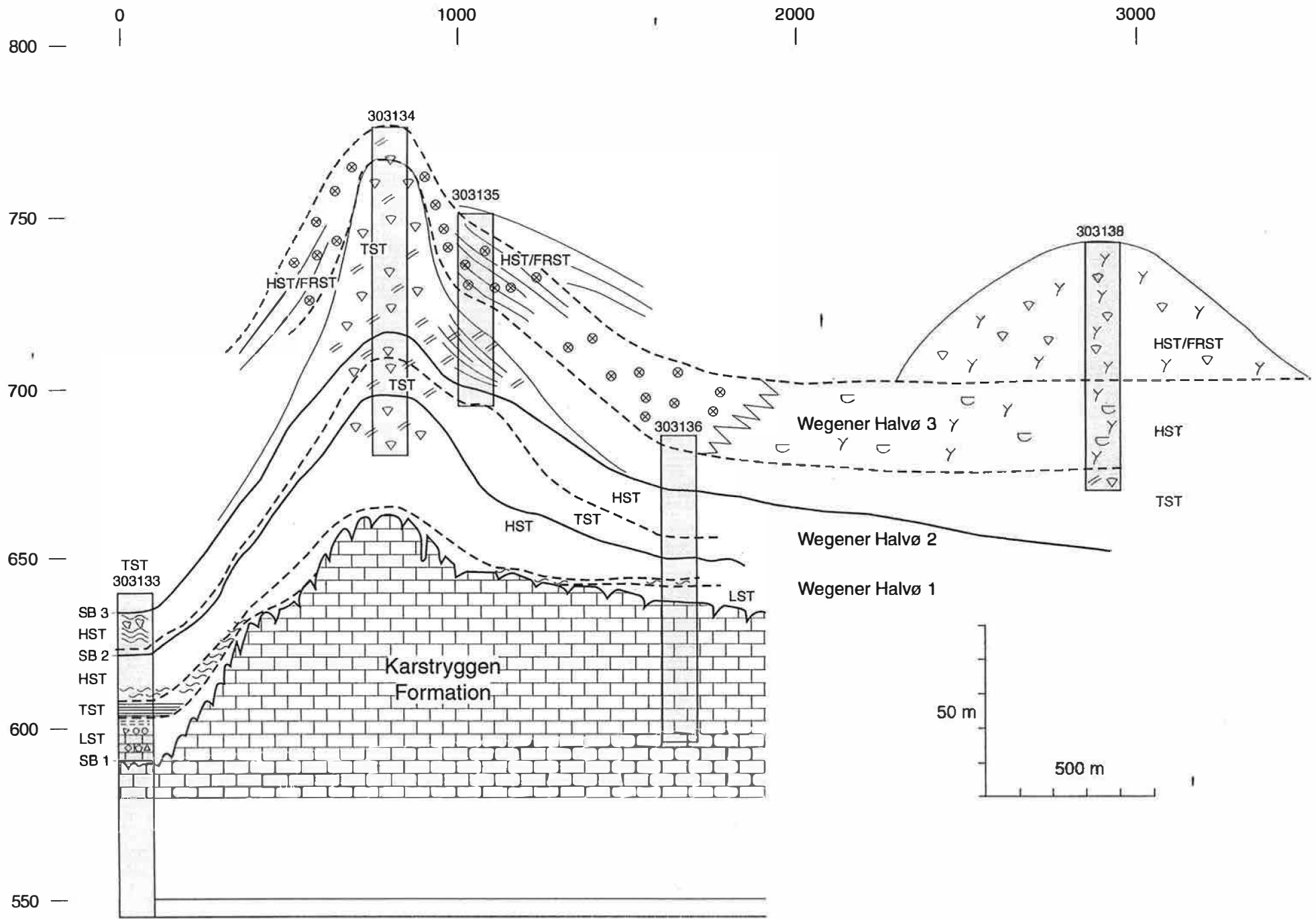


Fig. 4

303133

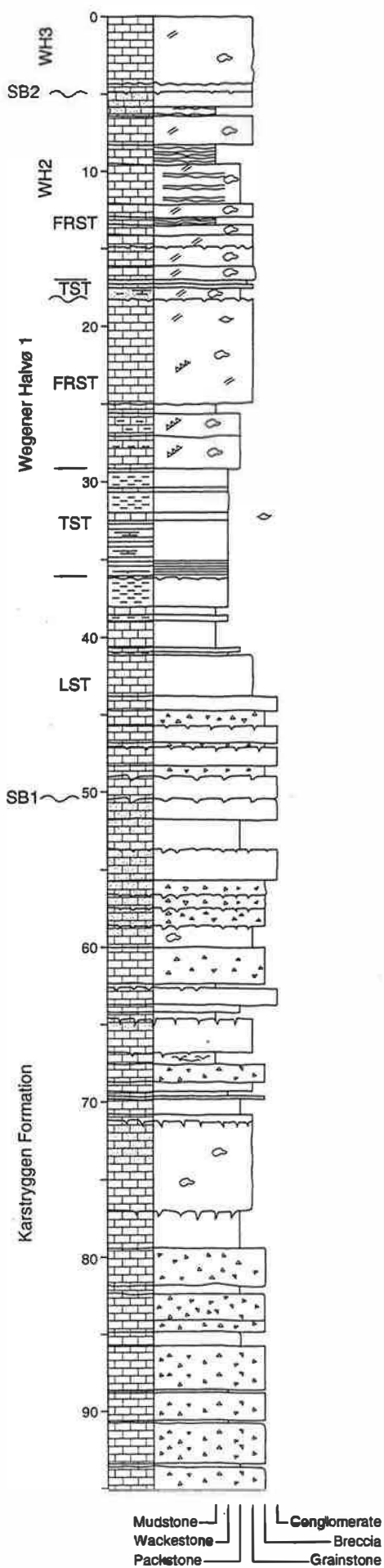


Fig. 5A

303134

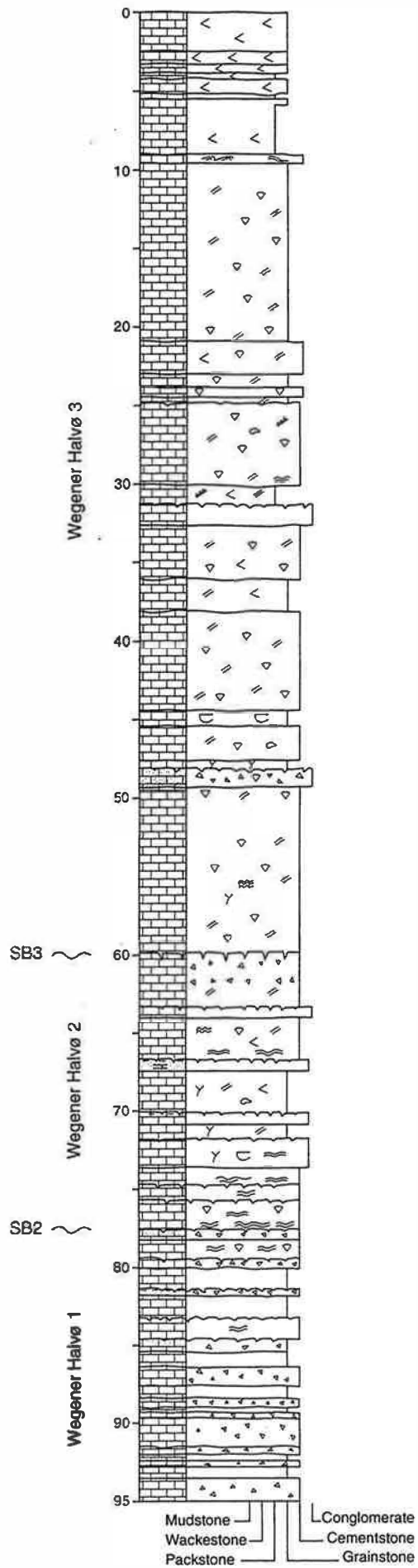


Fig. 5B

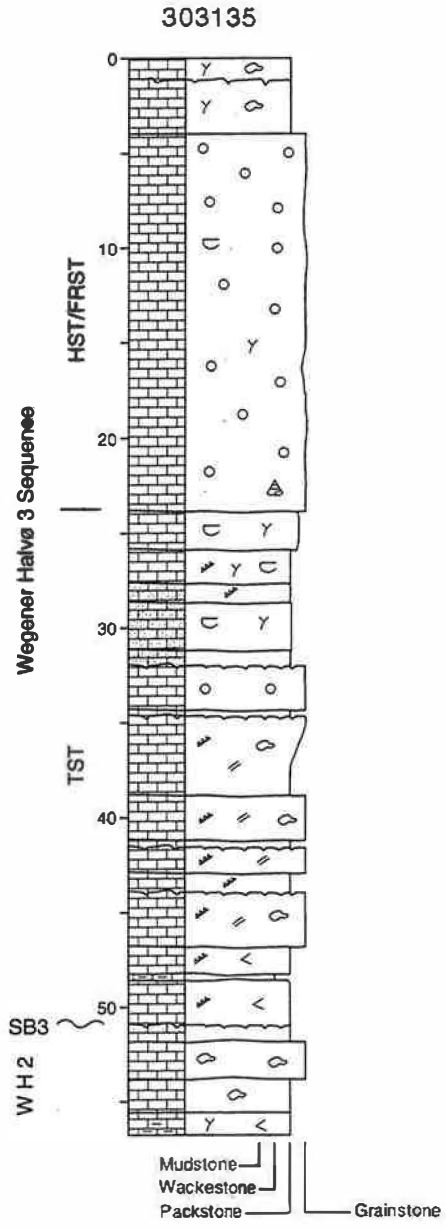


Fig. 5C

303136

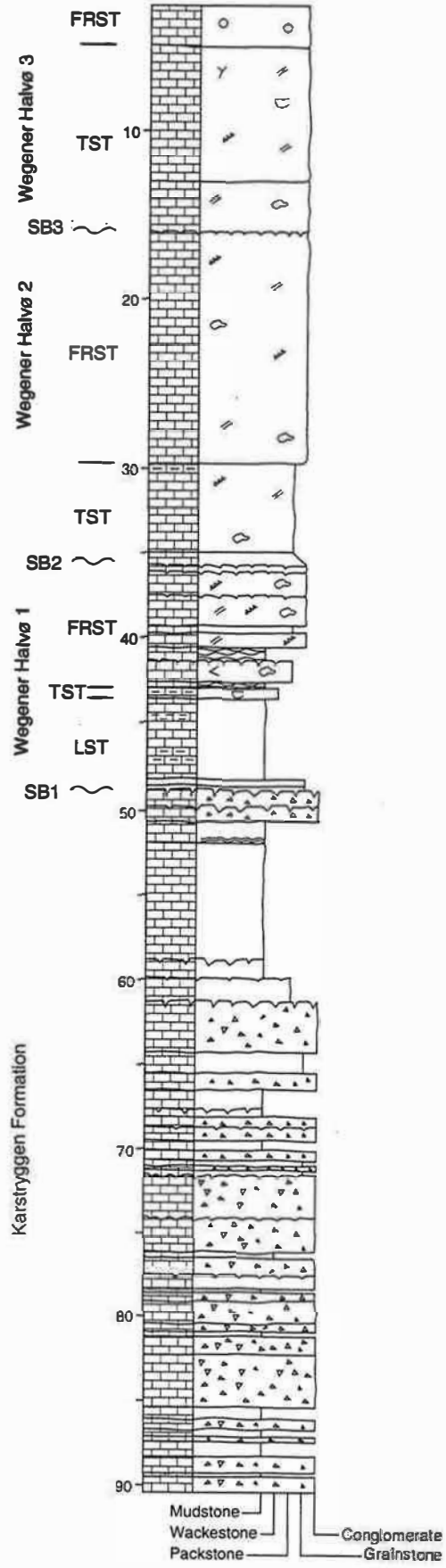


Fig. 5D

303137

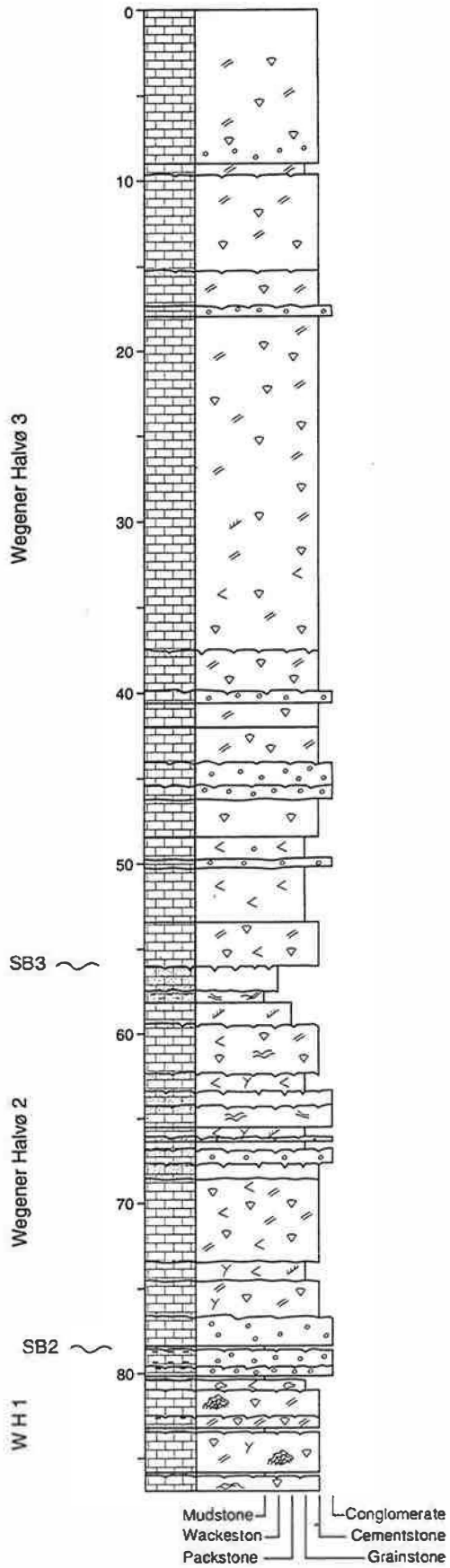


Fig. 5E

303138

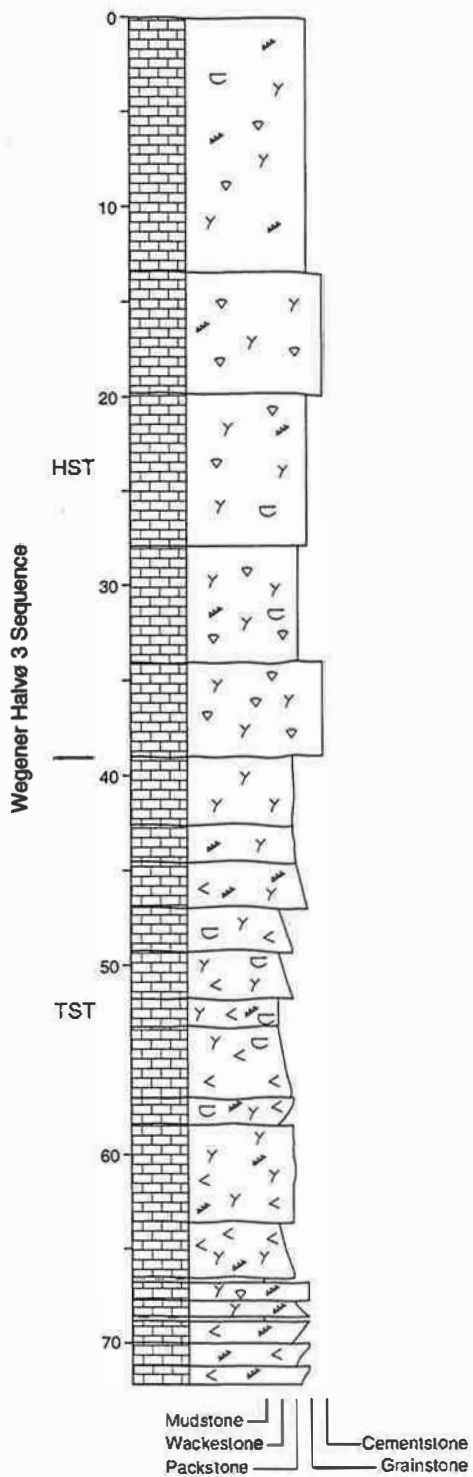
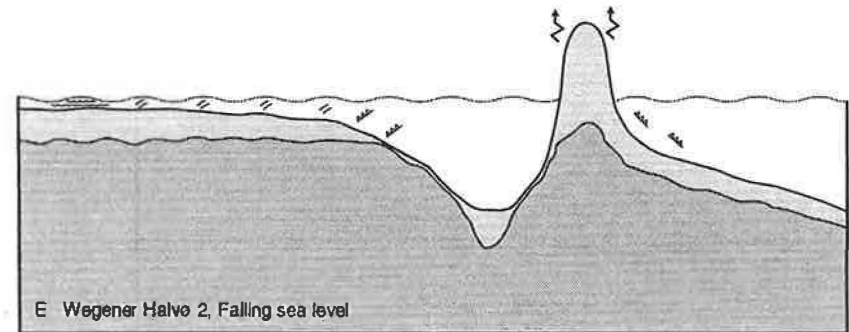
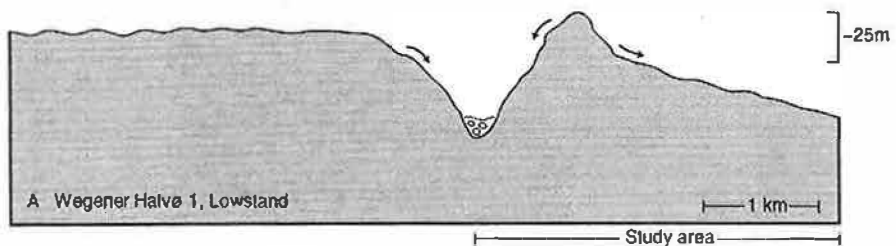
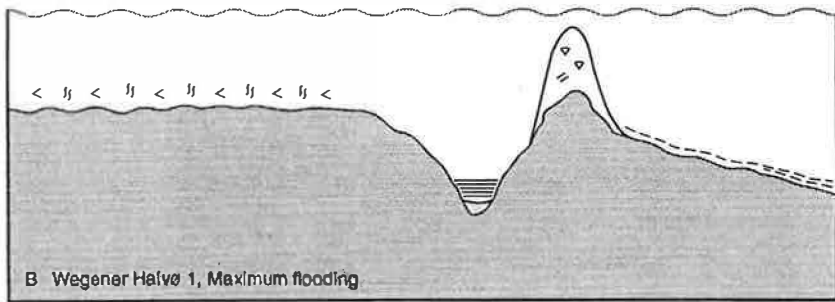
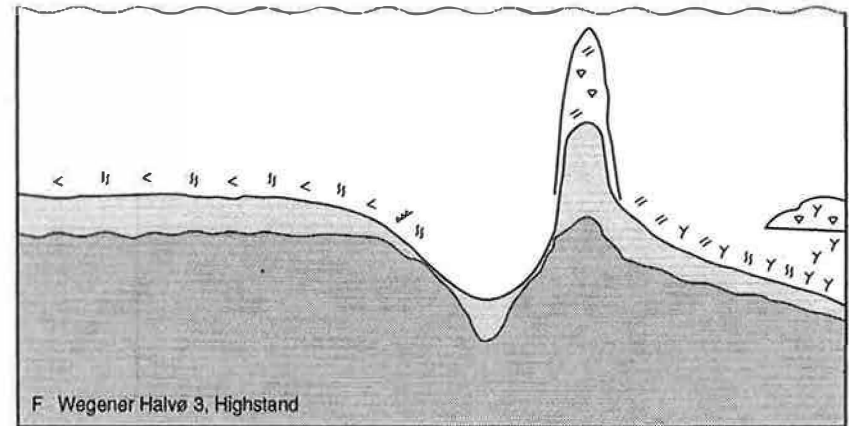
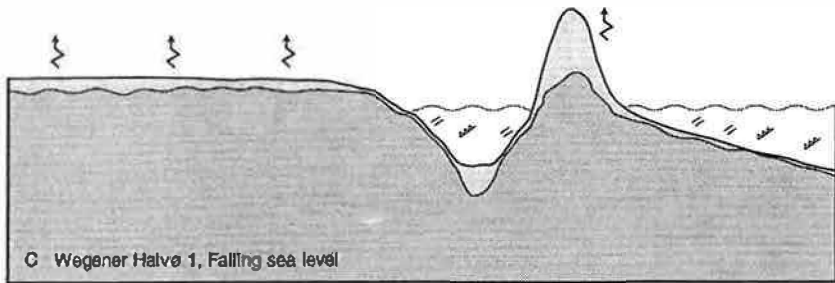
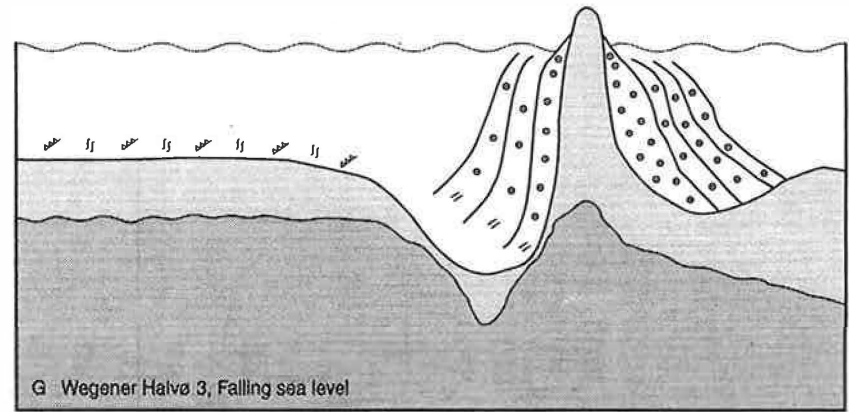
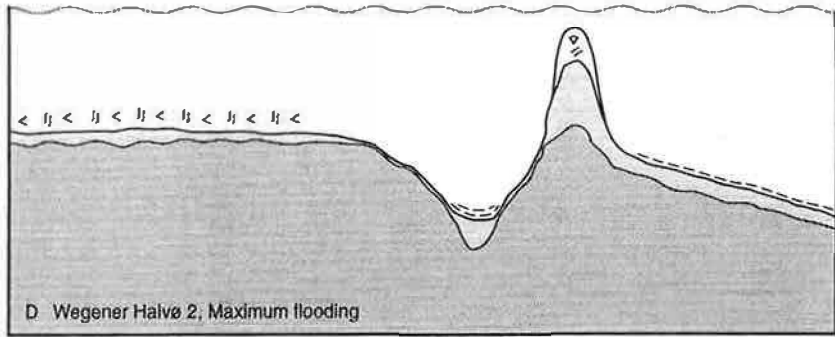


Fig. 5F



 Karstryggen Formation
  Wegener Halvø Formation

Fig. 6



Fig. 7

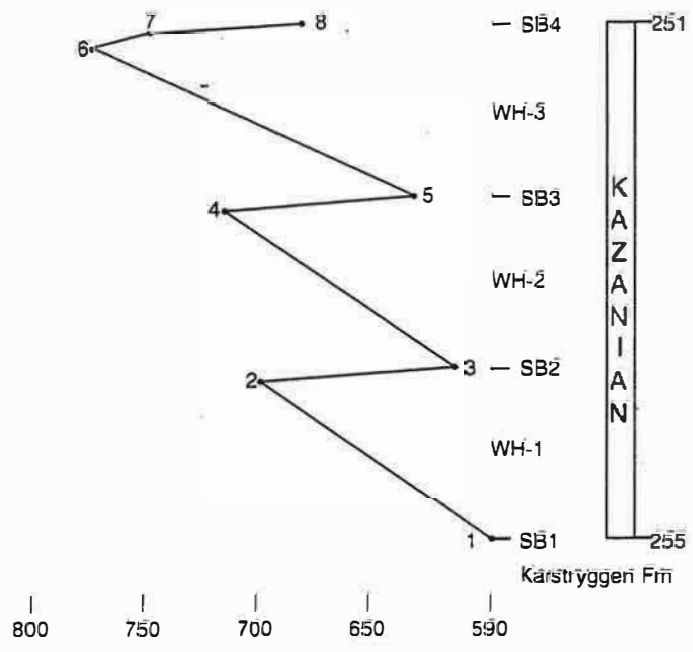


Fig. 8