# Guide to excursion in Bornholm

8th annual working meeting in Sweden and Denmark of Project Tornquist/Southwest border of the East-European Platform

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IGCP Project no. 86

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# I OUTLINE OF THE GEOLOGY OF BORNHOLM

by

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Bornholm is the easternmost island of Denmark and rather far away from the rest of the country (Fig. 1). Situated in the south-eastern part of the Fenno-Scandian Border Zone (Tornquist Line) with the Fenno-Scandian Precambrian Shield towards the north and the Danish-Polish Subbasin towards the south, Bornholm has a complex tectonic and sedimentological history (like Scania). The pre-Quaternary surface consists of Precambrian basement rocks in the northern part of the island, whereas Palaeozoic and Mesozoic sediments, often separated from the basement by faults, are found in the western and southern part (Fig. 2). The pre-Quaternary rocks are all covered by Quaternary deposits, mainly tills and melt water sediments.

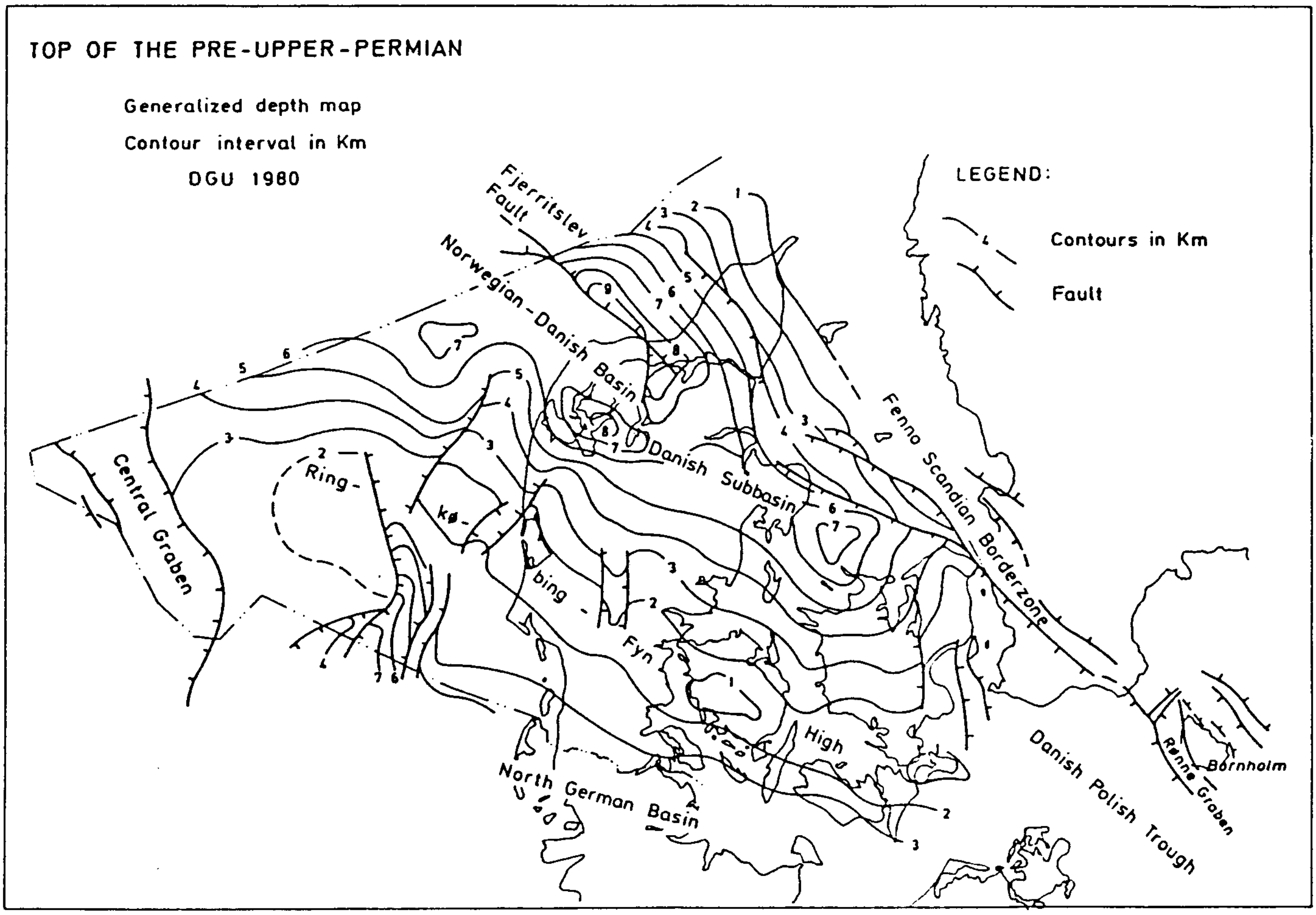



Fig. 1. Schematic palaeotectonic map of Denmark with adjacent area. Bornholm is the island situated just east of the Rønne Graben (from Michelsen & Andersen 1981).

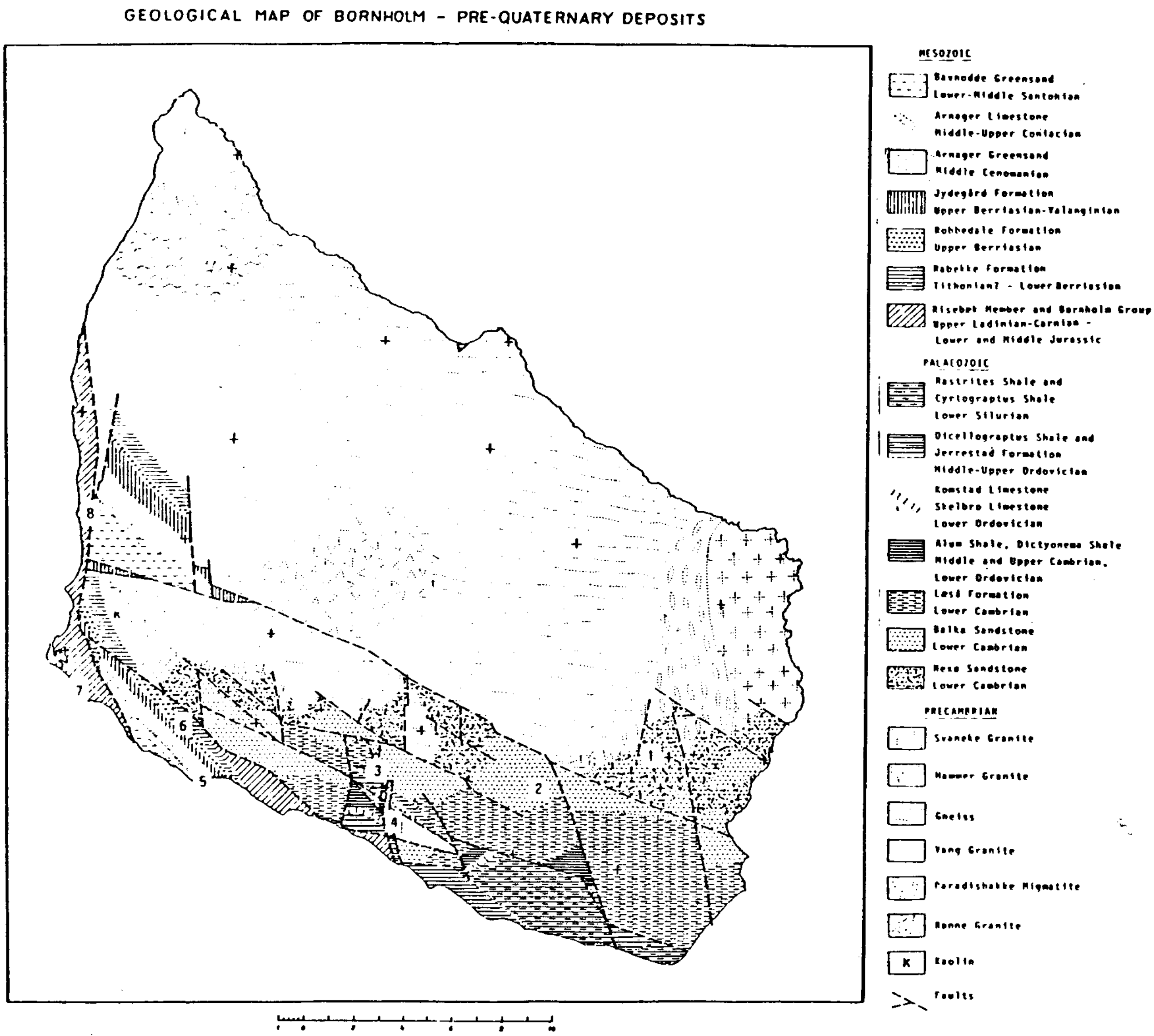



Fig. 2. Geological map of Bornholm - pre-Quaternary deposits (after Gry 1960, but with a new legend).

*Precambrian basement*

The Precambrian basement consists mainly of crystalline granitic and gneissic rocks. The age of the rocks varies between 1255 and 1390 MA (Larsen 1971, Larsen & Springer 1976). The rocks are younger than the main Svecofennian orogeny but older than the Dalslandian orogeny. The various rock types have local names, and the distribution is shown in fig. 2.

The gneiss (streaky granite or gneissic granite) is the dominant rock type. It is grey, medium-grained and contains the dark minerals (biotite, hornblende) concentrated in the thin streaks. The Paradisbakke Migmatite (Paradisbakke Gneiss), from the area Paradisbakkerne, is a fine-medium-grained rock type with dark streaks which are almost identical with the Rønne Granite and light-coloured streaks related to leucogranitic veins.

Dark granitic types are known from an area northeast of the town Rønne: Rønne Granite (Rønne Granodiorite), which is medium-grained, dark grey and contains hypersthen.

Light-coloured granites are known from various parts of the island. The reddish-grey Svaneke Granite, from the area around the town Svaneke is the only coarse-grained granite and a variety of this type is named the Hallegård Granite. The Vang Granite in the northern part of the island between Vang and Tejn is a medium-grained, dark grey granite with a reddish tinge (microcline). Hornblende and biotite occur in small clusters. The Hammer Granite in the northernmost part of Bornholm around Hammeren and in the Almindingen area is a medium-grained reddish grey rock with spots of red colour (hematite?).

Besides the main rock types other basement rocks are found in lesser amounts. These include veins and lenses of pegmatites, aplites, and leucogranites and dykes of olivine diabases.

The basement is rather poor in inclusions, but folded quartzites, phyllites, leptitic gneisses (Noe-Nygaard 1957), skarn (Callisen 1956), feldspathic sandstones and volcanic rocks (Jørgart 1977) are found. The age relationship between the different rock types are not easy to determine, but at present the following chronology is accepted: The oldest rocks are the small inclusions, which represent the original sedimentary and volcanic rocks. Then follows the gneissic and migmatitic rocks and lastly the granites, which are the youngest plutonic rocks. Finally diabases have intruded zones of weakness in the other basement rocks. They do not cut through the Palaeozoic and Mesozoic sediments and thus are dated as Precambrian (Münther 1973). Palaeomagnetic dating of dykes from northeastern Bornholm (Abrahamsen 1977) however, indicate at least three generations of dykes: one intruded shortly after cooling of the Svaneke Granite (1200 MA), a second intrusion 1000 MA ago, and finally a third event which possibly is of Lower-Mid Palaeozoic age.

| Chronostratigraphy | | Lithostratigraphy | |
|---|---|---|---|
| System | Serie | Danish onshore area | Bornholm |
| Permian | Zechstein | Rock salt, Limestone evaporites | |
| Permian | Rotliegendes | Sandstone, siltstone, claystone, vulcanic rocks | |
| Carbonife-rous | Upper | | |
| Carbonife-rous | Lower | Limestone, marlstone, mudstone | |
| Devonian | | | |
| Silurian | Ludlowian | Sandstone<br>Siltstone<br>Clay stone<br>Vulcanic rocks | |
| Silurian | Wenlockian | | Graptolite Mudstone (Cyrtograptus) |
| Silurian | Llandoverian | Siltstone<br>Shale | Cyrtograptus<br>Graptolite Mudstone<br>Rastites |
| Ordovician | Ashgillian | | Dalmanitina Beds<br>Jerrestad Fm. |
| Ordovician | Caradocian | | Dicellograptus Shale |
| Ordovician | Llandeilian | | |
| Ordovician | Llanvirnian | | |
| Ordovician | Arenigian | | Komstad Limestone<br>Skelbro Limestone |
| Ordovician | Tremadocian | | Dictyonema Shale |
| Cambrian | Upper | Alum Shale | Alum Shale |
| Cambrian | Middle | | Andrarum Limestone<br>Alum Shale<br>Exsulans Limestone / Borregård Mb. – Kalby Mb. |
| Cambrian | Lower | Mudstone<br>Sandstone | Læså Fm.: Rispebjerg Sandstone, Broens Odde Mb.<br>Balka Sandstone / Hardeberga Sandstone<br>Nexø Sandstone |
| Precambrian | | Gneiss | Gneiss, granite, diabase |

Fig. 3. Stratigraphical scheme of the Precambrian and the Palaeozoic of the Danish onshore area and Bornholm.

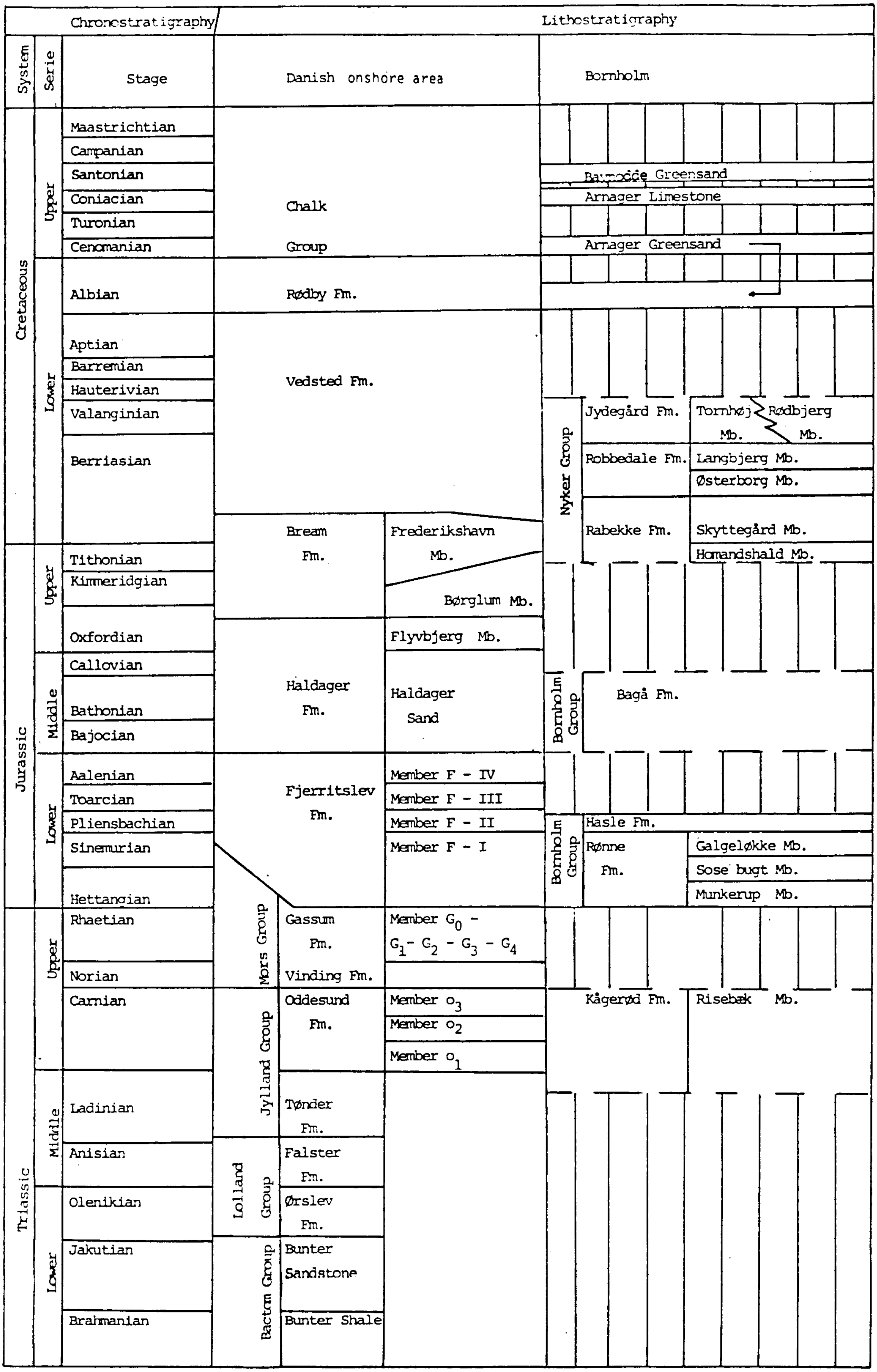



Fig. 4. Stratigraphical scheme of the Mesozoic of the Danish onshore area and Bornholm.

*Palaeozoic deposits*

The Palaeozoic sequence on Bornholm is about 500 m thick and comprises Cambrian, Ordovician, and Silurian deposits (Fig. 5). The sediments were formed on the relatively stable Precambrian platform and consist of a rather uniform sequence, mainly dark grey mudstones and shales with minor limestone intercalations. The succession is in many ways related to that of Scania. However, the Early Palaeozoic sequence on Bornholm is rather incomplete, with several sedimentation breaks, and the beds are usually thinner than in the neighbouring regions. This is presumably a result of separate uplifts of the area of Bornholm throughout the Early Palaeozoic.

To the south the Precambrian basement is overlain by the 100 m thick Early Cambrian (Tommotian) subarkosic, fluviatile, mainly red colored Nexø Sandstone. This sequence is overlain by the 60 m thick marine, occasionally glauconitic, quartzitic Balka Sandstone, deposited in tidal environment, and indicating the Early Cambrian transgression. The two sequences are correlated with the Hardeberga Sandstone in Scania. The formation is succeeded by the regressive Læså Formation, consisting of the Broens Odde Member ("Green Shales") ( Figs. 3, 6), a glauconitic; highly bioturbated siltstone with phosphorite nodules. The sequence is followed by the 3 m Rispebjerg Sandstone, with well rounded quartz grains and terminated by a phosphorized horizon, indicating a hiatus.

Middle and Late Cambrian, and Early Ordovician rocks of Bornholm are dominated by anoxic black claystones (alum shales) with subordinate limestone beds or lenses. A large number of phosphorite conglomerates indicate periods of non-deposition and/or regressions. The Middle Cambrian is initiated by the Exulans Limestone, comprising the max. 40 cm thick Kalby Member in Læså and the 1 m thick grey limestone sequence, Borregård Member, in Øleå. The phosphorized top is overlain by the 1.5 m thick "Lower Alum Shale", succeeded by a 25 cm anthraconite bed with a phosphorite conglomerate, which initiates the 1.5 m thick bituminous Andrarum Limestone. The Middle Cambrian sequence is terminated by the 2 m thick lowermost part of the "Upper Alum Shale", which passes into the 21 m thick Upper Cambrian alum shale, "Olenid Shale", a homogene black shale with scattered large anthraconite lenses.

CAMBRIAN - SILURIAN ON BORNHOLM

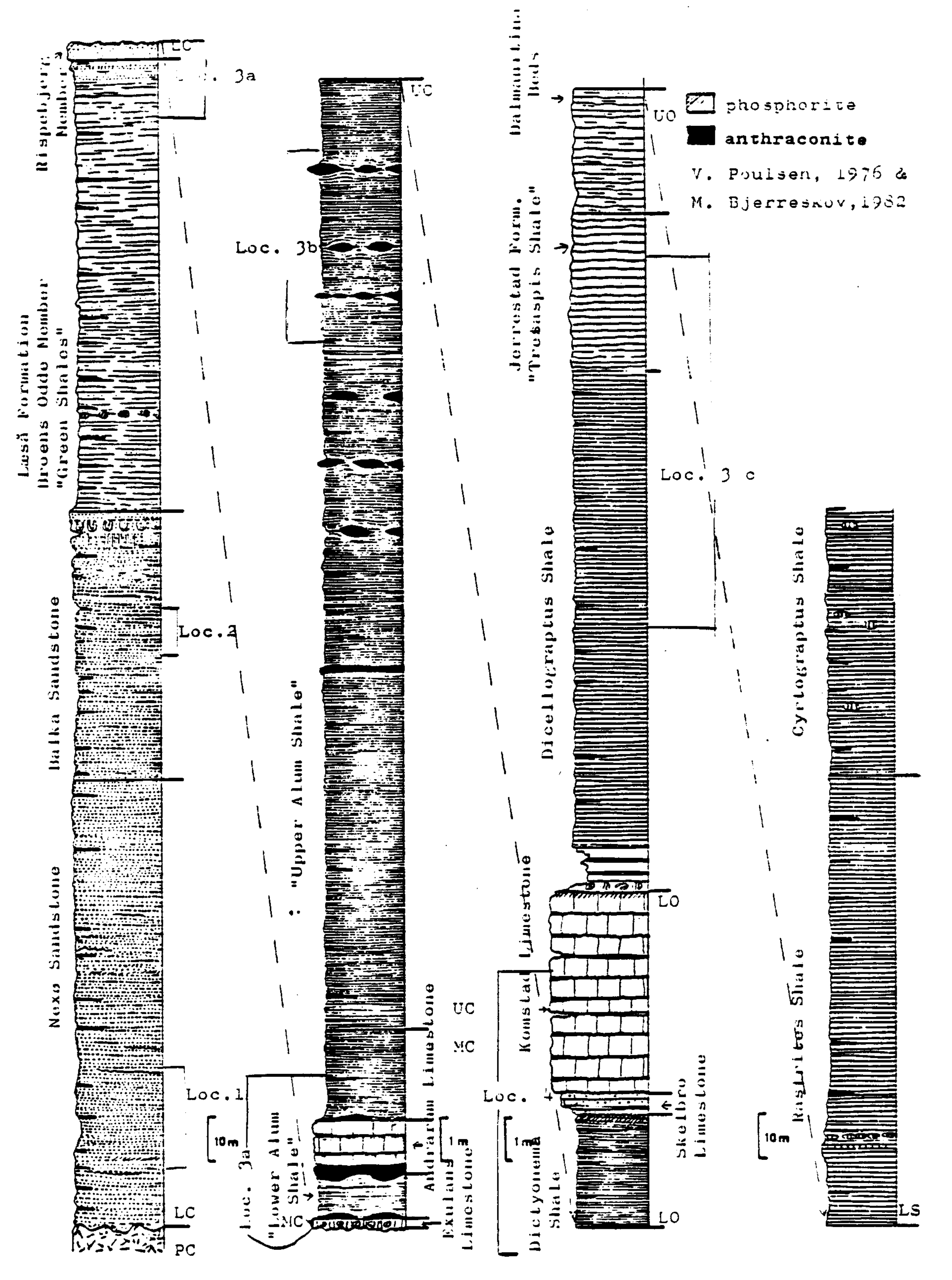



Fig. 5. Section of the Cambrian-Silurian deposits of Bornholm (after V. Poulsen 1976, Bjerreskov 1982).

## THE CAMBRIAN OF BORNHOLM

| Series | | Stages or zonal groups | Zones | Lithologic divisions |
|---|---|---|---|---|
| Upper | Olenid Series | | Acerocare | Alum Shale with anthraconite lenses |
| | | | *Peltura scarabaeoides* | |
| | | | *Peltura minor* | |
| | | | *Protopeltura praecursor* | |
| | | | *Leptoplastus* | |
| | | | *Parabolina spinulosa* & *Orusia lenticularis* | |
| | | | *Homagnostus obesus* & *Olenus* | |
| | | | *Agnostus pisiformis* | |
| Middle | Paradoxides Series | Paradoxides forchhammeri | *Lejopyge laevigata* | |
| | | | *Solenopleura brachymetopa* | Andrarum Limestone |
| | | | *Ptychagnostus lundgreni* & *Goniagnostus nathorsti* | Anthraconite<br>Phosphorite conglomerate |
| | | Paradoxides paradoxissimus | *Ptychagnostus punctuosus* | Lower Alum Shale |
| | | | *Hypagnostus parvifrons* | |
| | | | *Tomagnostus fissus* & *Ptychagnostus atavus* | Exs. Lst. Form.: Borregård Member; Kalby Member (Pyr. bed, Marl. bed) |
| | | | *Triplagnostus gibbus* | |
| | | Eccaparadoxides oelandicus | *Eccaparadoxides oelandicus pinus* | |
| | | | *Eccaparadoxides insularis* | |
| Lower | Holmia Series | | *Proampyx linnarssoni* | |
| | | | *Holmia kjerulfi* | |
| | | | *Holmia* ? | Rispebjerg Sandstone Mb (Læså Form.) |
| | | | *Schmidtiellus mickwitzi* | (Broens odde MB)<br>("Green Shales") (Læså Form.) |
| | | | *Mobergella holsti* | Balka Sandstone; Hardeberga Sandstone |
| | | | | Neksø Sandstone |

Fig. 6. Cambrian stratigraphy of Bornholm (V. Poulsen, 1966; V. Poulsen, 1978; Berg-Madsen, 1981, and Bergström & Ahlberg, 1981).

# THE ORDOVICIAN OF BORNHOLM

| BRITISH SERIES | BALTO-SCANDIAN SERIES | | STAGES (Mainly shelly faces) | BIOZONES | | LITHOLOGIC DIVISIONS |
|---|---|---|---|---|---|---|
| Ashgillian | Upper | Harjuan | Hirnantian | *Brongniartella platynota* | | ? |
| | | | | *Dalmanitina mucronata* | | Dalmanitina Beds |
| | | | | *Dalmanitina olini* | | ? |
| | | | Jerrestadian | *Dicellograptus anceps* | *Staurocephalus clavifrons* | Jerrestad Formation (Brown Tretaspis Shale) |
| | | | | *Dicellograptus complanatus* | *Eodindymene pulchra* | |
| | | | Vasagaardian | *Pleurograptus linearis* | | Dicellograptus Shale |
| Caradocian | Middle | Viruan | | *Dicranograptus clingani* | | ? |
| | | | | ? | | Dicellograptus Shale |
| | | | | *Diplograptus multidens* | | |
| | | | | *Nemagraptus gracilis* | | |
| Llandeilian | | | Uhakuan | *Glyptograptus teretiusculus* | | |
| Llanvirnian | | | Lasnamagian<br>Aserian | *Didymograptus murchisoni* | | |
| | Lower | Oelandian | Kundan | *Didymograptus bifidus* | *Megistaspis gigas* | |
| | | | | | *Megistaspis obtusicauda* | |
| | | | | | *Asaphus raniceps* | |
| | | | | | *Asaphus expansus* | |
| Arenigian | | | Volkhovian | | *Megistaspis limbata limbata* | Komstad Limestone |
| | | | | *Didymograptus hirundo* | ? | |
| | | | | | *Megistaspis lata* | |
| | | | | | *Cyclopyge stigmata* | Skelbro Limestone |
| | | | Billingenian | *Phyllogr. angustifolius elongatus* | | |
| | | | | *Phyllograptus densus* | | |
| | | | | *Didymograptus balticus* | | |
| | | | Hunnebergian | *Tetragraptus phyllograptoides* | | |
| | | | | ? | | |
| Tremadocian | | | | *Apatokephalus serratus* | | |
| | | | | *"Shumardia"* | | |
| | | | | *Ceratiocaris?* Scania Beds | | |
| | | | Pakerortian | *Dictyonema norvegicum* & *Bryograptus kjerulfi* | | Dictyonema Shale |
| | | | | *Adelograptus hunnebergensis* & *Clonograptus tenellus* | | |
| | | | | *Dictyonema flabelliforme* | | |
| | | | | *Dictyonema sociale* | | |
| | | | | *Dictyonema desmograptoides* | | |

Fig. 7. Ordovician stratigraphy of Bornholm (V. Poulsen, 1966; V. Poulsen, 1978; Bergström & Nilsson, 1974; von Janson, 1979 and preliminary results, persn. comn., A. Nielsen, 1982).

THE SILURIAN OF BORNHOLM

| Series | Graptolite zones | | | |
|---|---|---|---|---|
| | British sequence | Bornholm | Scania | |
| | Ricards (1976) | Bjerreskov (1975) and this paper | | Laufeld et al. (1975) and Nilsson (1979) |
| Ludlow | | | Öved-Ramsåsa Group | |
| Ludlow | *Bohemogr.* proliferation | | Öved-Ramsåsa Group ? | |
| Ludlow | *M. leintwardinensis* | | Colonus Shale | ? (most probably developed) |
| Ludlow | *M. tumescens* | | Colonus Shale | ? (most probably developed) |
| Ludlow | *L. scanicus* | | Colonus Shale | *C. scanicus* |
| Ludlow | *N. nilssoni* | | Colonus Shale | *N. nilssoni* |
| Wenlock | *M. ludensis* | | Colonus Shale | *P. ludensis* |
| Wenlock | *G. nassa* | | Cyrtograptus Shale | *G. nassa/P. dubius* |
| Wenlock | *C. lundgreni* | *C. lundgreni* | Cyrtograptus Shale | *C. lundgreni* |
| Wenlock | *C. ellesae* | | Cyrtograptus Shale | ? *C. radians* |
| Wenlock | *C. linnarssoni* | | Cyrtograptus Shale | "*C. rigidus*" |
| Wenlock | *C. rigidus* | | Cyrtograptus Shale | "*C. rigidus*" |
| Wenlock | *M. riccartonensis* | | Cyrtograptus Shale | *M. riccartonensis* |
| Wenlock | *C. murchisoni* | | Cyrtograptus Shale | *C. murchisoni* |
| Wenlock | *C. centrifugus* | *C. centrifugus* | Cyrtograptus Shale | *C. murchisoni* |
| Llandovery | *M. crenulata* | *C. lapworthi* | Cyrtograptus Shale | *M. crenulata* |
| Llandovery | *M. crenulata* | *M. spiralis* | Rastrites Shale | ↑ |
| Llandovery | *M. griestoniensis* | *M. griestoniensis* | Rastrites Shale | |
| Llandovery | *M. crispus* | *M. crispus* | Rastrites Shale | |
| Llandovery | *M. turriculatus* | *M. turriculatus* | Rastrites Shale | |
| Llandovery | *R. maximus* | *M. turriculatus* | Rastrites Shale | |
| Llandovery | *M. sedgwicki* | | Rastrites Shale | |
| Llandovery | *M. convolutus* | *M. convolutus* | Rastrites Shale | |
| Llandovery | *M. argenteus* | *C. gregarius*: ? | Rastrites Shale | |
| Llandovery | *D. magnus* | *C. gregarius*: *M. pectinatus* | Rastrites Shale | |
| Llandovery | *M. triangulatus* | *C. gregarius*: *M. triangulatus* | Rastrites Shale | |
| Llandovery | *C. cyphus* | *M. revolutus* | Rastrites Shale | |
| Llandovery | *L. acinaces* | *C. vesiculosus* | Rastrites Shale | ↓ |
| Llandovery | *A. atavus* | *L. acinaces* | Rastrites Shale | |
| Llandovery | *O. acuminatus* | *O. acuminatus* | Rastrites Shale | |
| Llandovery | *G. persculptus* | *G. persculptus* | Rastrites Shale | *G. persculptus* |

Fig. 8. Silurian stratigraphy of Bornholm. (Modified from Bjerreskov & Jørgensen, in press).

The Lower Ordovician (Tremadocian) is characterized by the incoming of *Dictyonema* and initiated by the 3.9 m thick alum shale, "*Dictyonema* Shale", which is terminated by a phosphoritized 5 cm thick horizon.

After a considerable hiatus a 15 cm thick phosphorite conglomerate initiates the 40 cm thick biomicritic Arenigian Skelbro Limestone. Separated by an omission surface (hiatus?) the 4.5 m thick biomicritic dark grey Arenigian Komstad Limestone follows.

There is a hiatus comprising the Llanvirnian and the main part of the Llandeilian, and above a 15 cm thick phosphorite conglomerate, the 12 m thick very dark grey claystone, the "*Dicellograptus* Shale" follows, of Late Llandeilian and Caradocian Age. The successive Jerrestad Formation (*Tretaspis* Shale), Caradocian-Ashgillian, is a 4.5 m thick light grey mudstone. The overlying Ashgillian 2-6 m thick *Dalmanitina* Beds, reported from a well, comprises grey mudstone and a coquina, and terminates the Ordovician regressive sequence.

The Silurian is commenced by the Llandoverian 135 m thick transgressive dark grey mudstone ("*Rastrites* Shale"), continuously followed by a 25 m thick dark grey mudstone sequence ("*Cyrtograptus* Shale") of only lowermost Wenlockian Age. There are no records of Middle Wenlockian deposits. The youngest Silurian strata comprise ?25 m dark grey silty mudstone ("*Cyrtograptus* Shale") which is exposed on the seafloor at the southeast coast. This sequence was probably deposited in a deeper basin. Late Silurian deposits have not yet been observed in situ on Bornholm.

Deposits of Devonian, Carboniferous and Permian ages are not known on Bornholm.

*Mesozoic deposits*

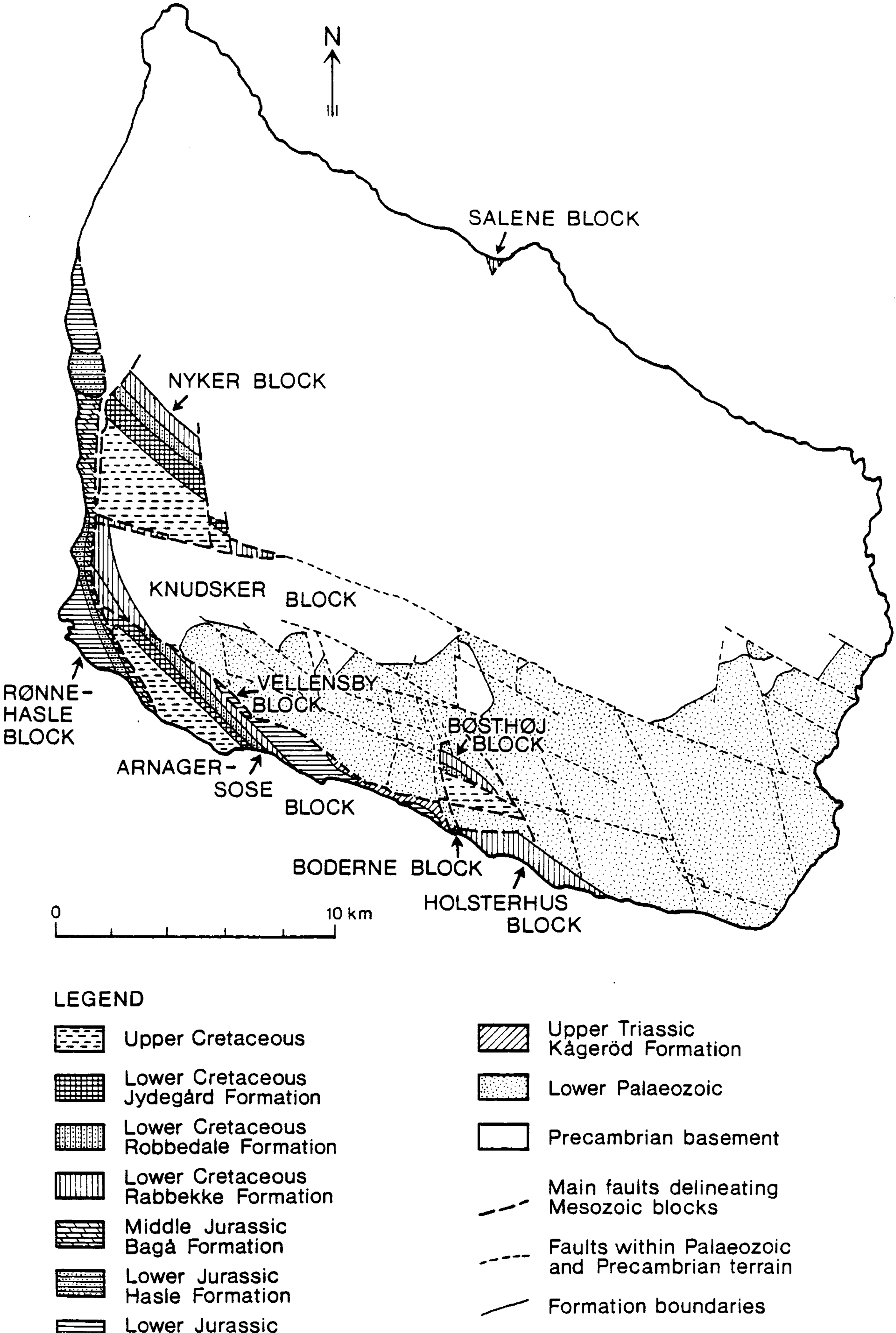
On Bornholm Early and Middle Triassic sediments are absent, and the Triassic is represented only by the Late Ladinian-Carnian Risebæk Member, which is conveniently placed in the Kågeröd Formation (Fig. 4) by Gravesen, Rolle & Surlyk (1982). The Risebæk Member (at least 60-70 m thick, Gry 1977a) consists of red, gren and grey green clay and silt with calcitic or siliceous caliche nodules which are reworked and deposited as pebble conglomerates or basal channel lags (Fig. 11). The clay alternates with beds of white or greenish sandstone. The trace fossils *Skolithos* and *Teichichnus* and oligohaline ostracods occur scattered. The member was mainly continental and deposited on a very flat and featureless terrain, as indicated by the scattered occurrence of the marine horizons (Surlyk 1980). Rhaetian sediments are absent, possibly caused by non-deposition or erosion, but sediments of this age are probably present in the deep grabens west and south of Bornholm.

The Jurassic begins with the Rønne Formation, which is subdivided in the Munkerup (base), Sose Bugt and Galgeløkke (top) Members (Fig. 4). The Early Hettangian Munkerup Member (approximately 20 m thick) consists of grey and black clay with subordinate sandstone beds and abundant carbonaceous detritus and plant fossils. The member is deposited under lacustrine conditions directly on the Risebæk Member or Cambrian quartzite.

The Munkerup Member is overlain by the Hettangian-? Sinemurian Sose Bugt Member (approximately 40 m thick) and is dominated by rapidly alternating beds of fine-grained cross-laminated sand and laminated clay. Rootlet horizons and thin coalseams are frequent and large channels are also found. Marine trace fossils *(Skolithos)*, wave-worked beds and heteroliths occur on the top. The lower part of the member is interpreted as a lower delta plain while the marine beds on the top demonstrate that the Hettangian-Sinemurian transgression continued (Gravesen et al. 1982).

The Sose Bugt Member is followed by the Sinemurian Galgeløkke Member (150-210 m thick). The lithology is mainly cross-laminated fine-grained sand or heterolithic wavy and flaser-laminated sand-clay with subordinate large scale cross-bedded medium to coarse-grained sand. The trace fossils *Skolithos* and *Planolites* are locally abundant. Autochtonous coal beds overlying dark clay with rootlets are found. The member is interpreted as a general regressive tidal flat complex of sandy and muddy flats, major tidal channels and coal bearing marsh (Sellwood 1972, 1975; Rolle 1977).

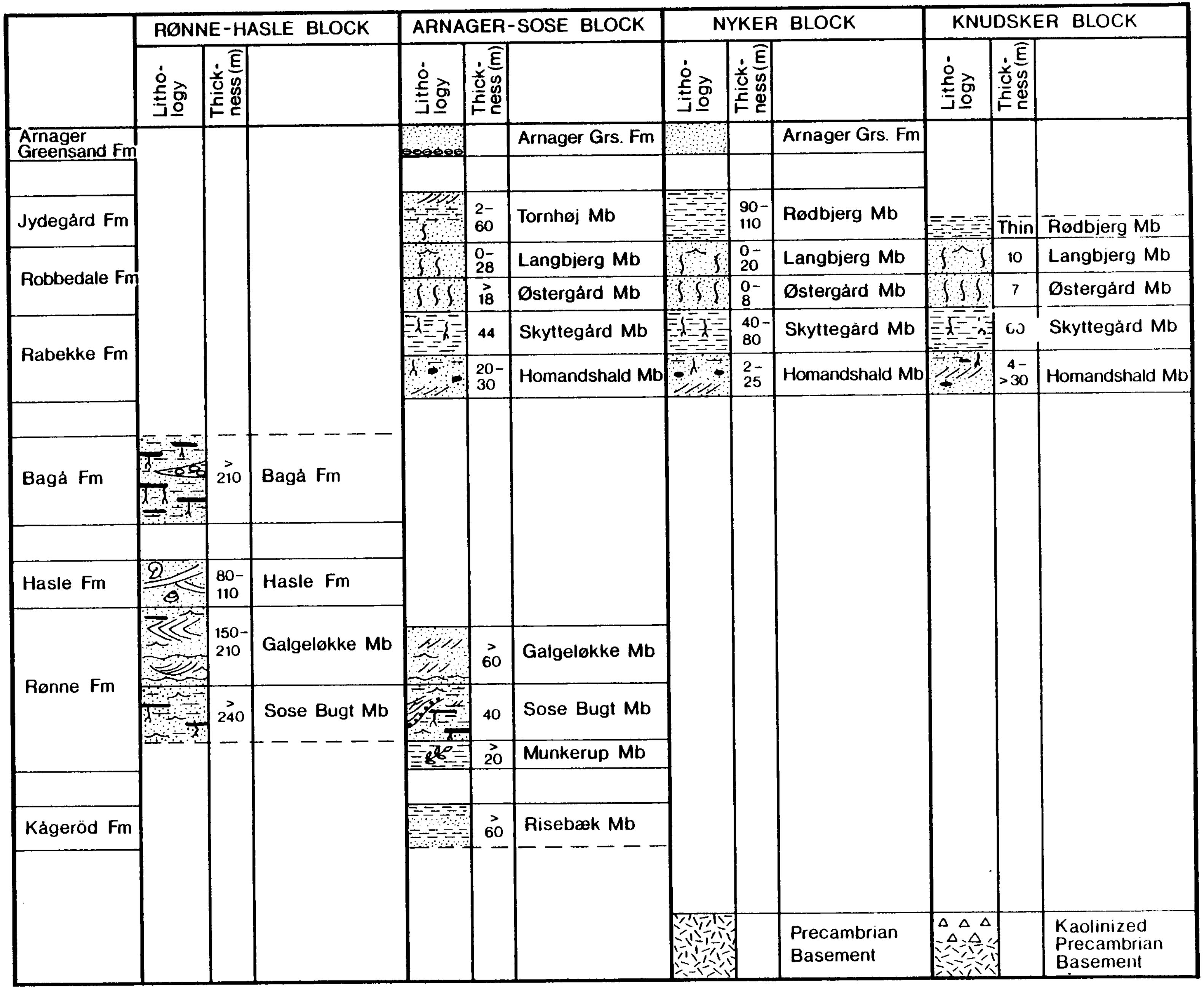
The Early Jurassic transgressions on Bornholm continued in Early Pliensbachian with deposition of the fully marine Hasle Formation (80-110 m thick). The formation is dominated by limonitic fine-grained sandstone, which is horizontally laminated or low angle trough cross-bedded, in places with gravelly laminae




Geological map of Bornholm. Modified from Gry (1960, 1969).

Fig. 9. Geological map of Bornholm showing the distribution of the Mesozoic deposits (from Gravesen et al. 1982).

Fig. 10. Scheme showing the Triassic - lowermost Upper Cretaceous sequences on the four main fault blocks of Bornholm (from Gravesen et al. 1982).




Scheme showing the Triassic – Lower Cretaceous sequences on the four main fault blocks of Bornholm.

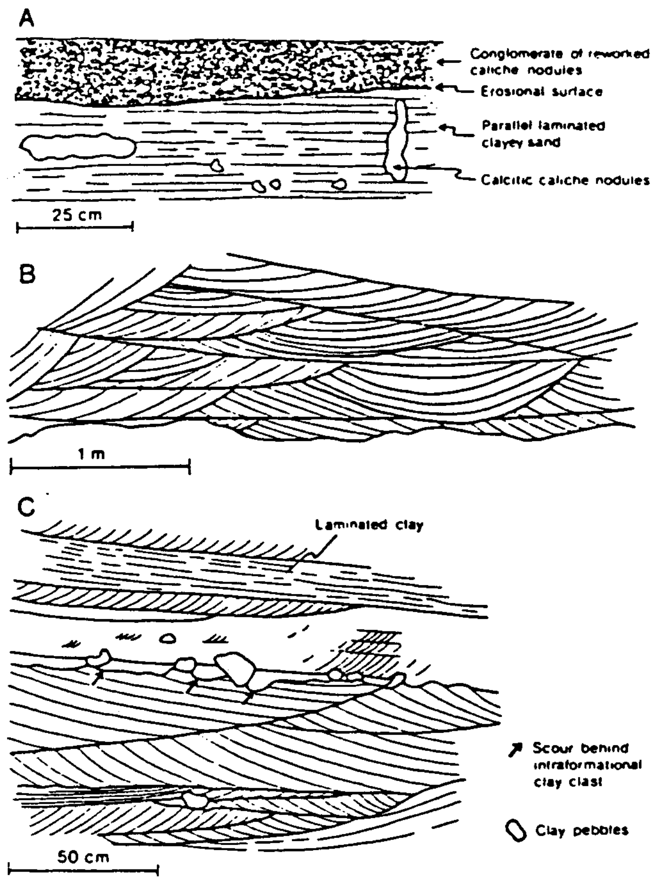
and erosive gravel beds with shell fragments. In the lower part of the formation occur beds of greenish grey, brown and grey clay with clay-ironstone. A rich fauna has been collected from the formation containing brachipods, bivalves, gastropods, belemnites, fish, and plesiosaur remains. Approximately ten ammonite species relate the formation to the zones of *Uptonia jamesoni* and *Prodactylioceras davoi* (Malling & Grönwall 1909, Höhne 1933). The depositional environments were the beach and foreshore with sand sedimentation and the shallow shelf with deposition of sand and mud (Rolle, Koch, Frandsen & Surlyk 1979).

On Bornholm there has been a pre-Bajocian hiatus corresponding to the Toarcian and Aalenian and the Middle Jurassic (Bajocian-Bathonian) Bagå Formation (more than 270 m thick) overstep different older strata (e.g. Silurian shales). The formation consists of fine- and coarse-grained cross-bedded sand, heteroliths, clay and coal seams with rootlets arranged in fining upwards cycles. Conglomerates are known from various localities. The regressive formation was deposited in a lower delta plain with a system of meandering channels, levees and backswamps and under marginal marine condition with clay deposition in interdistributary bays.

During the Jurassic, where the climate was warm and humid an abundant koalinizing of Precambrian basement rocks and Palaeozoic and Jurassic sediments took place (Callisen 1934, Bondam 1967, Gry 1977a,b).

Then follows a third major mid-Mesozoic hiatus on the top of the Middle Jurassic as probably most of the Upper Jurassic is absent.

The mainly Early Cretaceous sedimentation is continued by deposition of the Rabekke Formation, which is subdivided in the Homandshald and Skyttegård Members (Fig. 4). The Tithonian? - Early Berriasian regressive Homandshald Member (from a few m to approximately 30 m thick) comprises poorly sorted coarse-grained sand and gravel with abundant kaolin, cross-bedded ferruginous sandstone and sandy clay with rootlets. The member rests on Precambrian basement, kaolin (Fig. 12), Palaeozoic sediments or on Lower Jurassic sand and clay and is deposited in a fluviatile environment. Then follows the Early-Late Berriasian Skyttegård Member (13-80 m thick) dominated by multicoloured structureless sandy clay with a very high content of fine-grained plant detritus and thick beds of horizontally deposited lignite (Fig. 13). Rootlets, siderite and pyrite are




Flood-plain clay and silt and channel sand in the Keuper of Bornholm. Caliche nodules occur scattered or in horizons and may be reworked and deposited as conglomerates or channel lags.

Fig. 11. Details of the Triassic Risebæk Member (from Surlyk 1980).

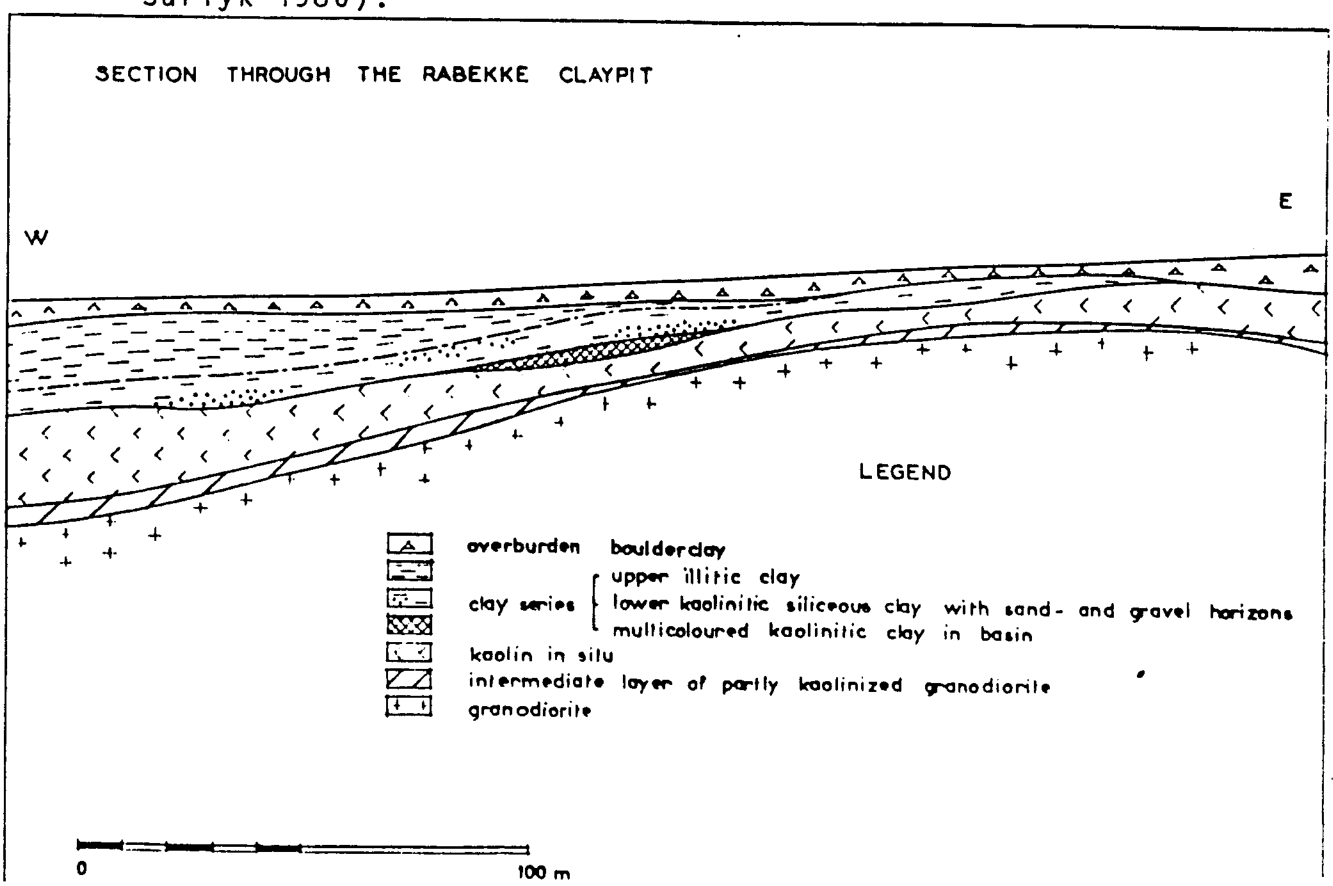
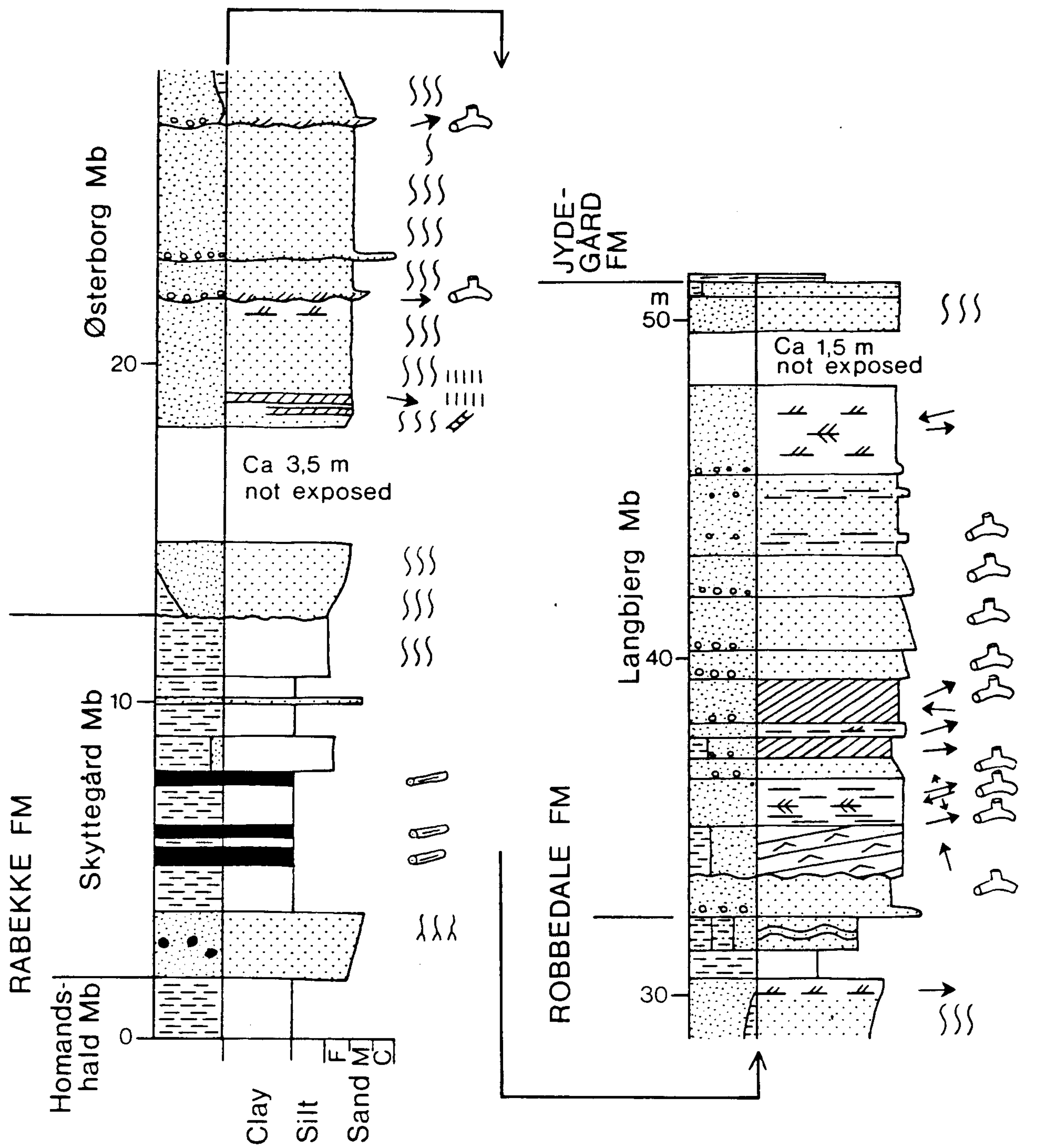



Fig. 12. Section through the Rabekke clay pit showing sediments of Rabekke Formation resting on kaolin (from Graff-Petersen & Bondam 1963)

common and ostracods, megaspores and plant fossils can be found. The clay is deposited in lacustrine and swamp environments, where the polyhaline ostracods show marginal marine conditions.

The sand-dominated Robbedale Formation, which is overlying the Skyttegård Member, represent the most marine stage in the broad regressive-transgressive-regressive pattern of the Early Cretaceous (Gravesen et al. 1982) and is subdivided in the Østerborg and Langbjerg Members (Fig. 4). The Late Berriasian Østerborg Member (4-18 m thick) is mainly fine-grained quartz sand characterized of galleries of *Ophiomorpha*, *Skolithos* and other trace fossils, which is deposited under transgressive conditions in the foreshore beach, on tidal sand flats, on shoals and in lagoons (Gravesen 1977, 1982). The Late Berriasian regressive Langbjerg Member (0-28 m thick) consists of medium to coarse-grained faintly horizontally laminated, bioturbated or cross-bedded quartz sand with *Ophiomorpha* and occasionally *Skolithos*, deposited on a prograding barrier island complex and on intertidal/subtidal channels and flats (Gravesen 1977, 1982).

This unit is conformably overlain by the regressive Late Berriasian - Valanginian Jydegård Formation which is subdivided into the interfingering Tornhøj and Rødbjerg Members. The Tornhøj Member (approximately 60 m thick) is characterized by rapid alternating of beds of quartz sand, silt, clay or clay-ironstone with abundant load-structures. The member contains concentrations of gastropods, bivalves and conchostracans and vertebrate remains and plant fossils occur scattered. The sediments are deposited in a lagoonal-lacustrine system in lagoons, back-barrier areas and washover fans. The Rødbjerg Member (90-110 m thick) is dominated by laminated sticky clay with subordinate sandstone, siltstone and clay-ironstone beds, but thick beds of silt and fine-grained silty sand often occur in the lower part of the member (Gravesen, Bakgaard & Villumsen 1980). Oolitic chamosite, pyrite and mica are characteristic and foraminifera, ostracods, gastropods, fish teeth, megaspores and plants occur in thin beds (Malling 1920, Gry 1956). The member represents the more central part of the Berriasian-Valanginian lagoonal-lacustrine system.



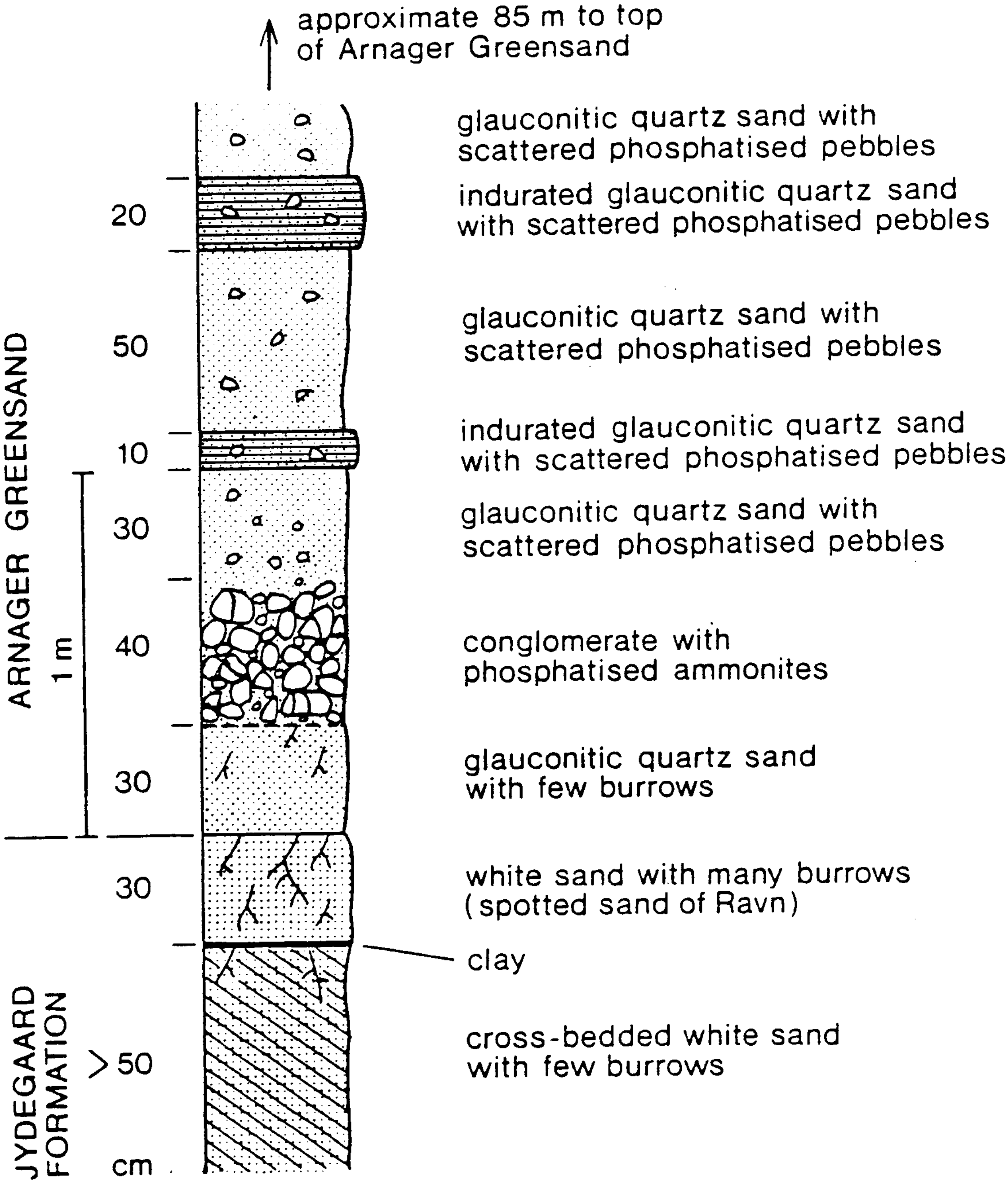

Type section of the Rabekke Formation and the Skyttegård Member, and reference section of the Robbedale Formation, Arnager Bugt. Position indicated by 3, 3b and 4 on fig. 27. Measured by P. Gravesen in 1976.

Fig. 13. Section of the Early Cretaceous Rabekke and Robbedale Formations, Arnager Bugt (from Gravesen et al 1982).

After deposition of the Jydegård Formation an important hiatus in the Mesozoic sequence follows, as the Hauterivian-Barremian and Aptian Stages all are absent, and the Jydegård Formation is unconformably overlain by the Early Middle Cenomanian Arnager Greensand, which is approximately 85 m thick (Kennedy, Hancock & Christensen 1980) (Fig. 14). Deposits of Early Albian and Early Cenomanian Age are represented as complex phosphatic nodules in a 0.6 m thick conglomerate at the base of the formation, where the two generations of pebbles are cemented by glauconitic sand. The mid-Cretaceous transgressions and regressions and the formation of the conglomerate are recently described by Kennedy, Hancock & Christensen (1980). The Arnager Greensand, which consists of loose, poorly sorted glauconitic fine-grained quartz sand, often silty or clayey with few horizons of cemented coarse-grained sand, was deposited probably on a shallow shelf under a Middle Cenomanian transgression. The sand is almost totally bioturbated and contains a fauna of ammonites, belemnites, bivalves, gastropods, brachiopods, and foraminifera.

Then follows a regressive period, with a hiatus comprising the Late Middle Cenomanian to Early Coniacian. The Middle-Late Coniacian Arnager Limestone (12-20 m thick), which lies unconformably on the intensively burrowed top of the Arnager Greensand, was deposited during a new transgression. The basal part of the formation is a 0.2 m thick horizon with a hardground and complex phosphorized intraclasts. The limestone has a low carbonate content, and is often strongly bioturbated with *Thalassinoides*. A fauna of ammonites, belemnites, brachiopods, echinoids, asteroids, foraminifera, and corals have been found.

The youngest known Mesozoic formation is the Early-Middle Santonian Bavnodde Greensand (180 m thick), which after a minor local regression was deposited under a transgression on the eroded upper surface of the Arnager Limestone. The formation is dominated by often clayey, glauconitic, fine-grained quartz sand occasionally cemented and with thin coarse-grained sandstone beds. The sand is strongly bioturbated with abundant trace fossils and a fauna of ammonites, belemnites, crustaceans, gastropods, bivalves, brachiopods, echinoids, serpulids, brachiopods, and foraminifera. The formation was deposited on a shallow




Section of the boundary between the Jydegaard Formation of Valanginian-Hauterivian age and the overlying Arnager Greensand Formation at Madsegrav. The phosphatized ammonites came from the conglomerate, and the unphosphatized ammonites came by and large from the two indurated glauconitic quartz sand beds.

Fig. 14. Section of the Early Cretaceous Jydegård Formation and the Late Cretaceous Arnager Greensand, Madsegrav, Arnager Bugt (from Kennedy et al. 1980).

shelf near a clastic shoreline and erosive, storm sand deposits, occur in several horizons in the sequence (Surlyk 1980).

The Mesozoic deposits of Bornholm proper are expected to be preserved in the deep grabens immediately west, south and possibly north of the island, but at present no detailed information is known about the sediments and their stratigraphy (Andersen, Larsen & Platou 1975, Kögler & Larsen 1979).

# II THE TECTONIC EVOLUTION OF BORNHOLM

by
*Peter Gravesen*

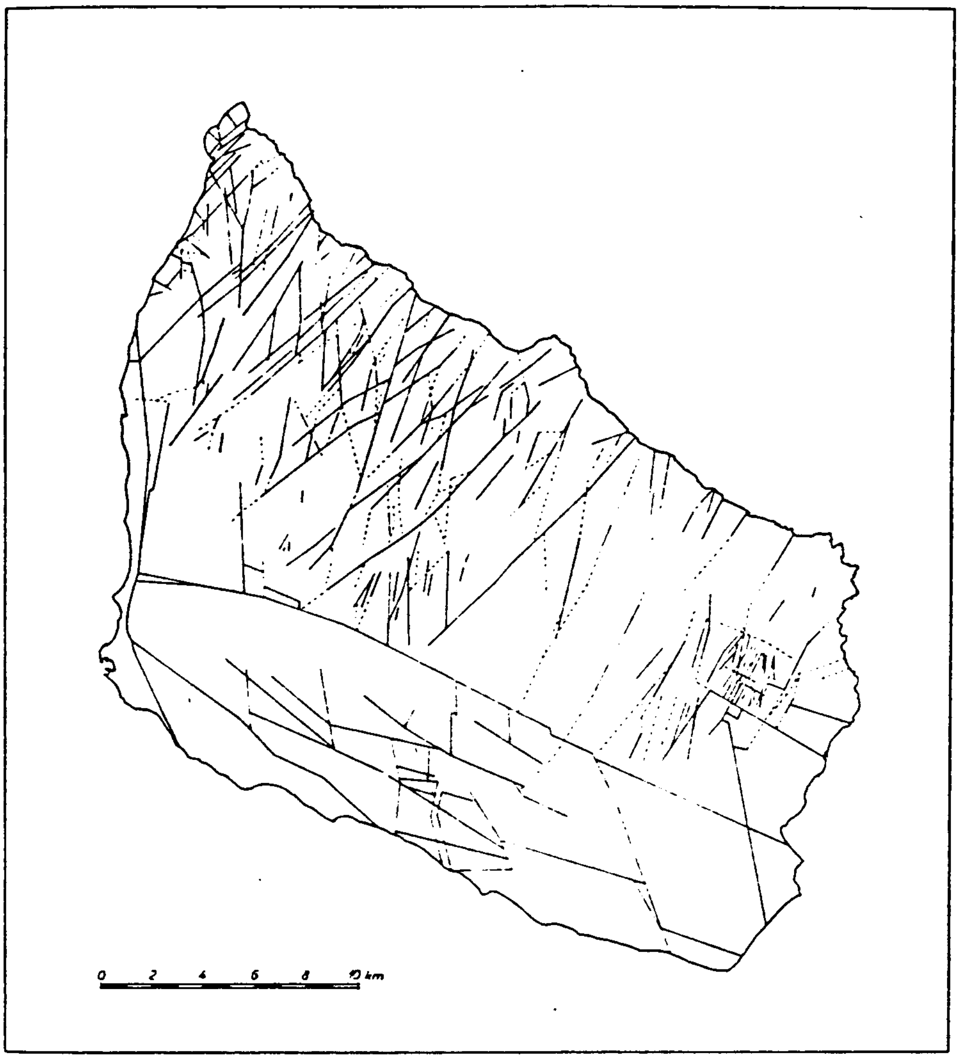
## *Precambrian tectonics*

The Precambrian basement forms structurally a single unit with few internal structures, and because of poor exposure it is difficult to outline the history of its formation. The Precambrian rocks and their genesis have been treated by e.g. Callisen (1934), Bubnoff & Kaufmann (1932, 1941), Micheelsen (1961), Noe-Nygaard (1963), and recently by Platou (1970, 1971) and Jørgart (1977).

The basement has passed through two different major tectonic phases: an orogenic phase (Gothian? Age) and a following cratonic phase. The first phase started with the deformation, melting and folding of the original sedimentary and volcanic rocks. Then followed the formation of the foliated gneissic rocks with recrystallisation, deformation and further folding. The foliation is mainly striking E-W and dipping rather steeply to the north.

Some granites were formed partly contemporaneously with the gneisses and others were formed later. New evidence (Jørgart 1977) shows that the granites were formed by anatextic melting of gneisses and sedimentary rocks, and that they are only slightly deformed.

After cooling and consolidation of the youngest granites the second tectonic phase took place. The basement complex was uplifted and large blocks were faulted. Movements occurred in strongly mylonized and brecciated zones, and the main fault lines can now be seen in the basement area as long rectilinear valleys (Fig. 15) carved out by glacier streams during the Pleistocene glaciations. Both horizontal and vertical displacements have been recognized. The dominating fault zones strike N-S and NE-SW and strike-slip movements from 600 m to 2500 m are proposed (Münther 1945, 1973). Strike-slip faults with a NW-SE orientation (the Tornquist line direction) are also known, and the major fault zone: the Blykobbe-Balka Zone has a displacement of at least 2500 m (Münther 1973). The Precambrian faults can be followed towards the south under the sedimentary




Forkastninger og lineære, gennemskærende dale på Bornholm. Kortet er dels baseret på H. Gry (1960), dels på Geodætisk Instituts målebordsblade.

Fig. 15. The major fault lines of Bornholm (from Micheelsen 1961).

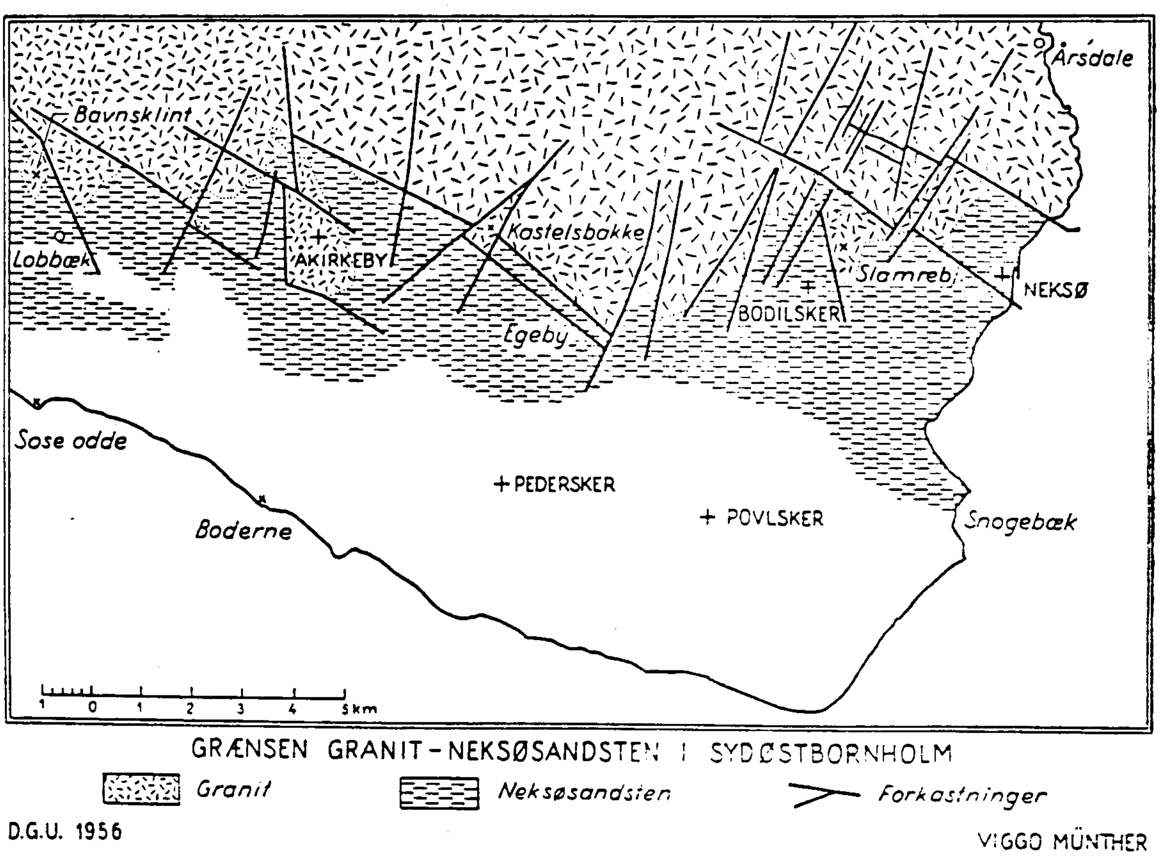



Fig. 16. Faults cutting the Precambrian basement and the Lower Cambrian Nexø Sandstone (from Münther 1957).

cover, and a few can be traced upwards into the sediments, where they have been re-activated during post-Precambrian time.

Apart from the large faults, the basement is cut by smaller joints of which the greater part form two steep sets orientated NNE-SSW and ESE-WNW (Bubnoff 1942).

Lastly, the olivine diabases were intruded into several of the sheared and brecciated fault zones and the directions are consequently the same as the faults. Formerly, they were thought to belong to a single period of intrusion, but several intrusive episodes probably took place as the dykes cut one another (Münther 1945, Noe-Nygaard 1963). They occur occasionally in dyke swarms and more than 200 dykes is registrated in all (Münther 1945, 1973). The dykes never penetrate into the sedimentary cover, and therefore the diabase intrusion is regarded as the last Precambrian event on Bornholm. There are indications however, that intrusions into Precambrian rocks also occurred during the Early-Middle Palaeozoic (Abrahamsen 1977).

*Palaeozoic tectonics*

The Lower Cambrian started with the sedimentation of sand on the strongly eroded and weathered Precambrian peneplain in continental and nearshore marine areas, and continued with deposition of marine clay, silt and limestone in the Middle-Late Cambrian, Ordovician and Silurian. The whole sequence is characterized by numerous hiati and periods of sedimentation, and can, according to Surlyk (1980), mainly be interpreted as a series of probably tectonically caused deepenings and transgressions followed by coastline progradations. The sediments are now cut by faults with WNW-ESE, NNW-SSE and N-S directions and this latter trend is probably of Late Palaeozoic age (Münther 1957, 1973). They can be followed into the Precambrian basement, which has been re-activated in the Late Palaeozoic (Fig. 16). Both normal faults and strike-slip faults have been registred, and a horizontal displacement of approximately 100-150 m is claimed by Münther (1957). The formation of the Fenno-Scandian Border Zone, can be documented back to Late Carboniferous-Early Permian (Michelsen & Andersen 1981), and Bornholm was faultet and uplifted during the Late Silurian - Late Carboniferous.

Volcanic activity in the area around Bornholm is in Ordovician and Silurian indicated by the occurrence of several thin bentonite beds and part of the diabas dykes on Bornholm can be of Early Palaeozoic age.

During the Late Silurian-Devonian-Carboniferous-Permian, Bornholm was a continental area dominated by erosion and weathering and this situation continued into the Early Mesozoic.

*Post-Palaeozoic tectonics*

The Mesozoic sedimentation and facies evolution on Bornholm is characterized by the interaction between eustatic sea-level changes and the Kimmerian and Laramide tectonic events.

In Early and Middle Triassic times, Bornholm still was uplifted and possibly exposed to erosion and weathering. First in Late Ladinian-Carnian Bornholm again became a depositional area with mainly continental sedimentation. The transition between the Triassic and the Jurassic is marked by the Early Kimmerian tectonic phase, which started in the Rhaetian with strongly block-faulting and erosion. Rhaetian sediments are absent. In Early Jurassic, local down-faulting of the blocks began such that the sediments overstep Keuper, Lower Palaeozoic and Precambrian rocks (Gry 1969), but the transgressions and deposition of deltaic and nearshore sediments in the Hettangian-Sinemurian-Early Pliensbachian are caused primarily by the Early Jurassic eustatic sea-level rise.

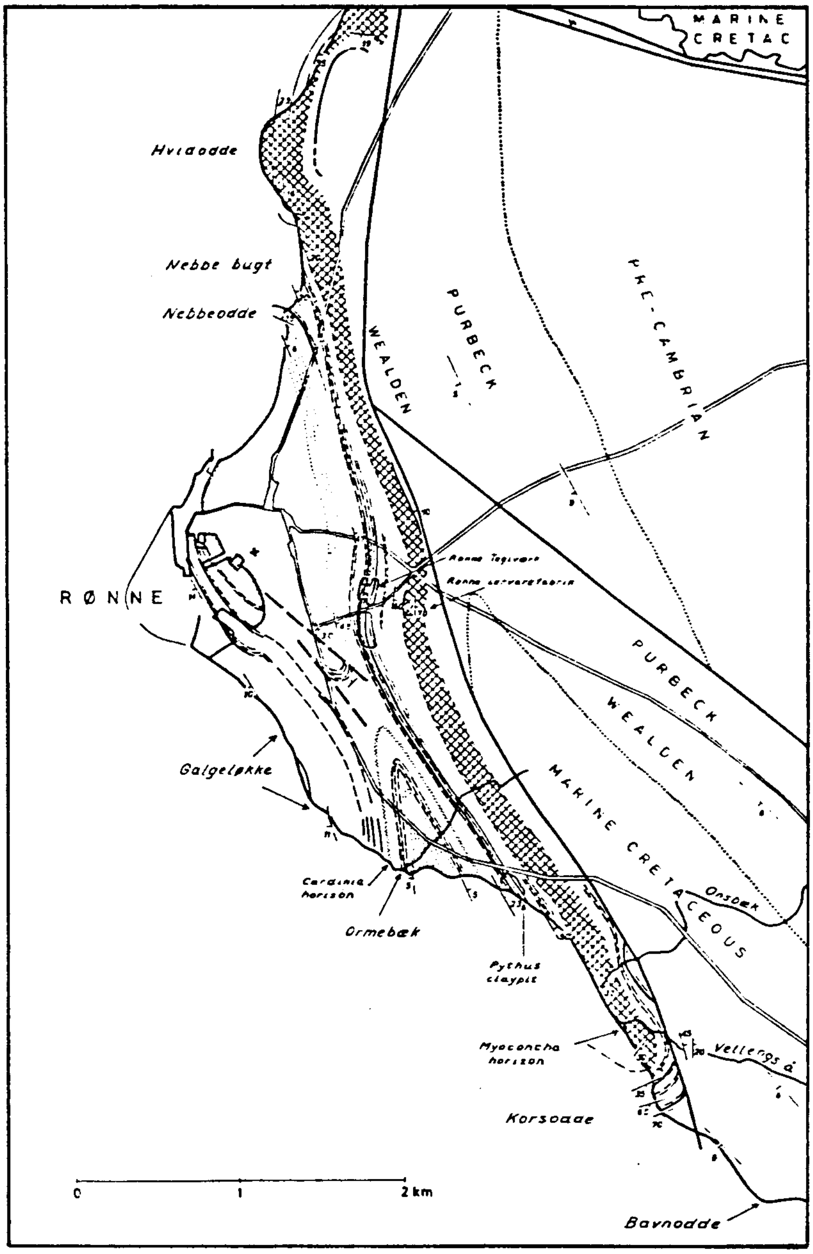
At the end of the Early Jurassic Bornholm was again uplifted, and the Mid Kimmerian tectonic phase accentuated new block-faulting. Toarcian and Aalenian sediments are absent, either because of erosion or non-deposition. In the Bajocian-Bathonian the sedimentation began in prograding deltas and with deposition of debris flow conglomerates from syn-sedimentary fault scarps. The deposits overstep Lower Jurassic and Palaeozoic sediments.

The Late Kimmerian phase is the major and most important tectnoc episode on Bornholm. During that phase, an intense block-faulting, tilting and erosion took place. Most of the Upper Jurassic is probably absent. The sedimentation, combined with the block-faulting, started in the ?Tithonian-Berriasian, where the deposits overstep Precambrian basement and Palaeozoic and Lower Jurassic sediments. The regressive-transgressive-regressive pattern in the Early Cretaceous is controlled by both the eustatic sea-level changes and the local tectonic disturbances, but a relatively continuous sedimentation is proposed during the ?Tithonian-Berriasian-Valanginian.

The sedimentation and basin evolution on Bornholm during the Late Triassic-Jurassic-Early Cretaceous follows the model proposed by Surlyk (1978), where stepwise transgression controlled by down-faulting of marginal blocks are accompanied by depositional regression. The NW-SE trending basin was extented progressively in a NE direction with gradual collapse and down-faulting along normal faults, but major faults also cutting the basin were active during this period of extension (Rolle et al. 1979, Gravesen et al. 1982).

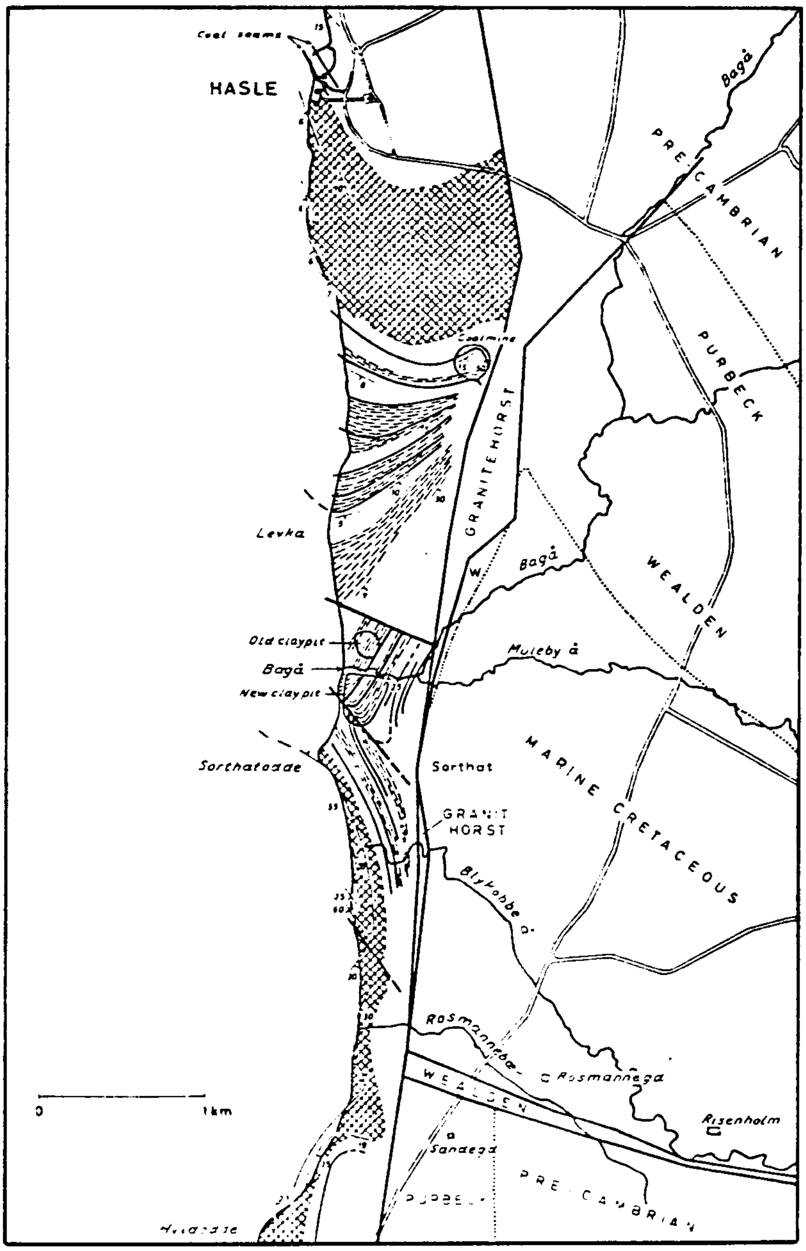
Bornholm was then elevated above sea-level and as a result of non-deposition or erosion a hiatus comprising the Hauterivian, Barremian and Aptian Stages follows. The deposition started again during the Albian-Cenomanian transgressions. The sediments rest with a slight angular unconformity on the Valanginian deposits, and the minor tectonic disturbance can possibly be related to the Austrian tectonic phase. The Late Cretaceous transgressions and regressions are caused primarily by general eustatic sea-level changes and local tectonic movements have only a minor influence (Kennedy, Hancock & Christensen 1980).

The most important tectonic episode concerning the present day distribution of the sediments is the Laramide phase, during which Bornholm was situated in a zone of inversion. The original extensional basin was deformed by wrench movements, whereby the sediments were folded and uplifted above erosional base level (Ziegler 1981). Thus, Bornholm was uplifted along faults, such that older strike-slip or normal fault lines, which bounded the sedimentary rocks, were re-activated. The Jurassic sediments west of the Rønne-Hasle fault line (Figs. 17, 18) were folded strongly and displaced towards north relative to the basement (Gry 1951, 1960, 1969, Münther, 1973), and geophysical measurements (Andersen et al. 1975) demonstrate that the basement is displaced 1500-2000 m downwards west of the fault and thus covered by a 1-2 km thick sequence of sediments in the Rønne Graben (Figs. 1, 23). In other fault blocks the sediments were normally



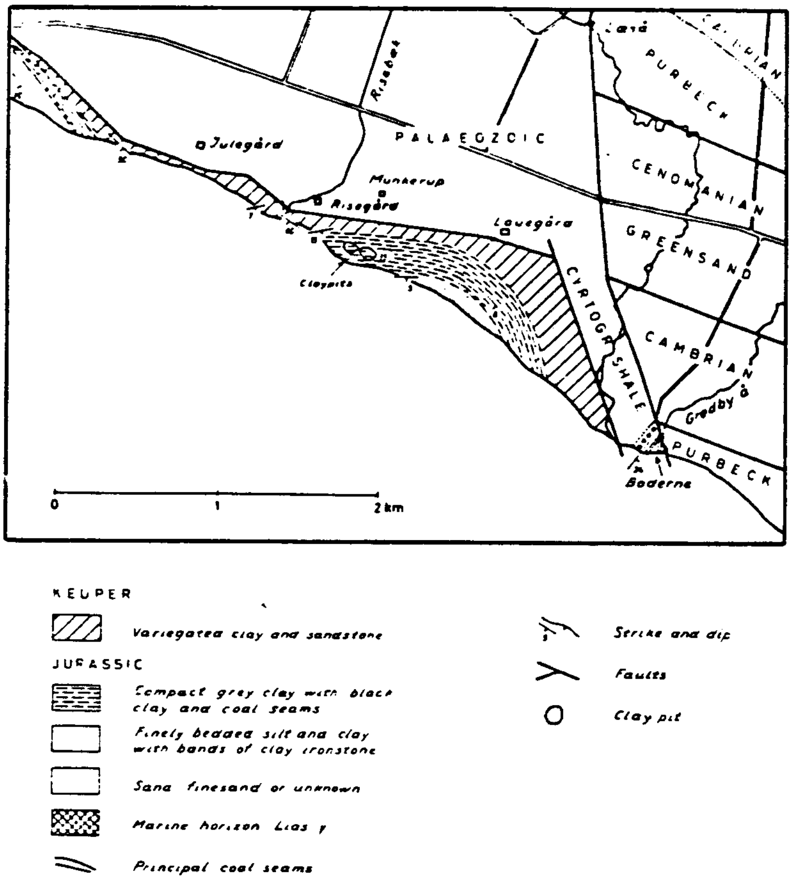

The Rønne area. Distribution of the sediment types in the Jurassic (somewhat simplified).

Fig. 17. Map showing the distribution and tectonics of the Early and Middle Jurassic Bornholm Group in the Rønne area, west of the Rønne-Hasle fault line. Legend Fig. 19 (from Gry 1969).




The Sorthat, Bagå and Levka-Hasle areas. Distribution of the sediment types in the Jurassic (somewhat simplified).

Fig. 18. The distribution and tectonics of the Jurassic Bornholm Group west of the northern part of Rønne-Hasle fault line. Legend fig. 19 (from Gry 1969).




The Munkerup-Risegård area and Boderne. Distribution of the sediment types in the Jurassic (somewhat simplified).

Fig. 19. The distribution and tectonics of the Triassic Risebæk Member (Keuper) and the overlying Early Jurassic Munkerup Member, south of the Rønne-Boderne Fault line (from Gry 1969).

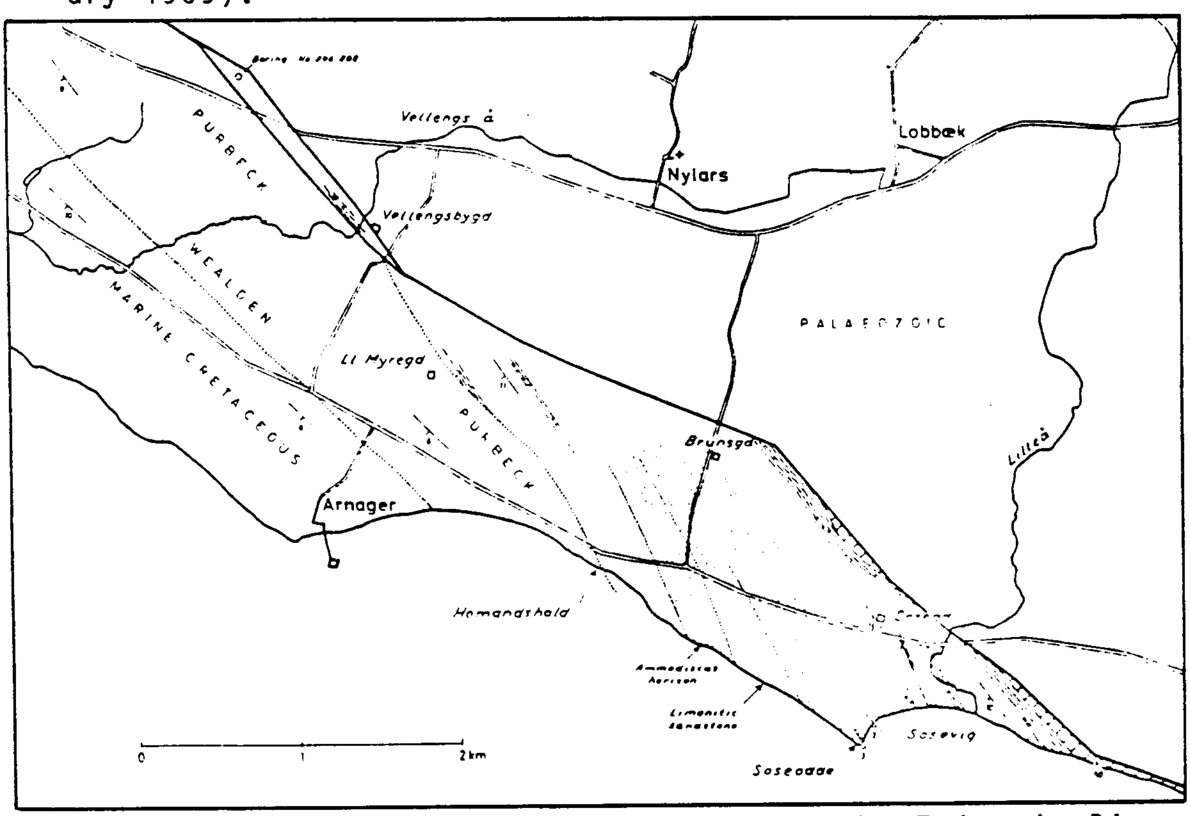



Fig. 20. The distribution and tectonics of the Triassic Risebæk Member and overlying Rønne Formation, south of the Rønne Boderne Fault line (from Gry 1969).

tilted only a few degrees towards the SE or S, but along some normal faults the beds have been strongly disturbed and vertically orientated (Gry 1977a) (Figs. 21, 22). Strike-slip movements are also known from e.g. the Rønne-Boderne fault where a displacement of 500 m has been estimated (Figs. 19, 20). A thrust fault is known from the Jydegaard-fault sliver, where the beds are vertically orientated (Gry 1960) (Fig. 24).

Several of the faults can be followed offshore Bornholm (Andersen et al. 1975, Kögler & Larsen 1979), where a system of horst and grabens have been demonstrated (Fig. 23). The complex mosaic of small fault blocks and slivers, which are especially found in the southern and eastern part of the island, result from a long tectonic history of syn-sedimentary and post-sedimentary faulting of both normal extentional and strike-slipe origin. The downfaulting and tilting of these blocks has protected the Palaeozoic and Mesozoic sediments from later Tertiary and Quaternary erosion.

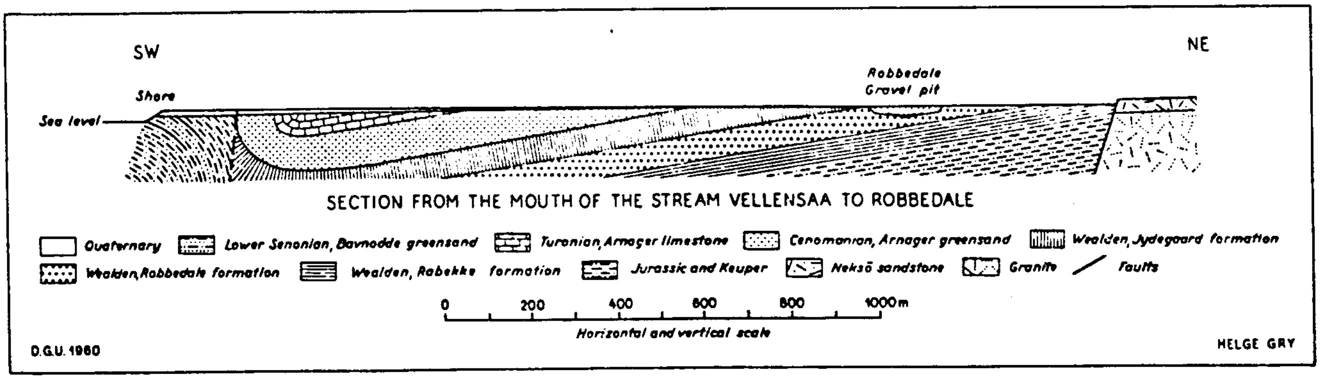
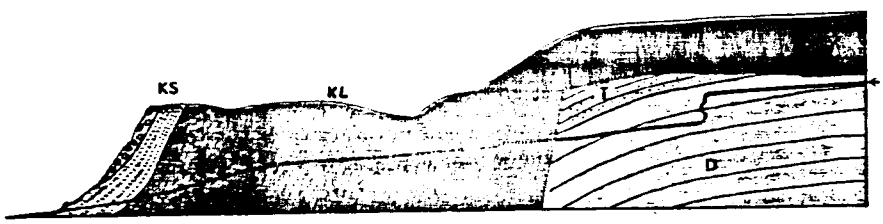
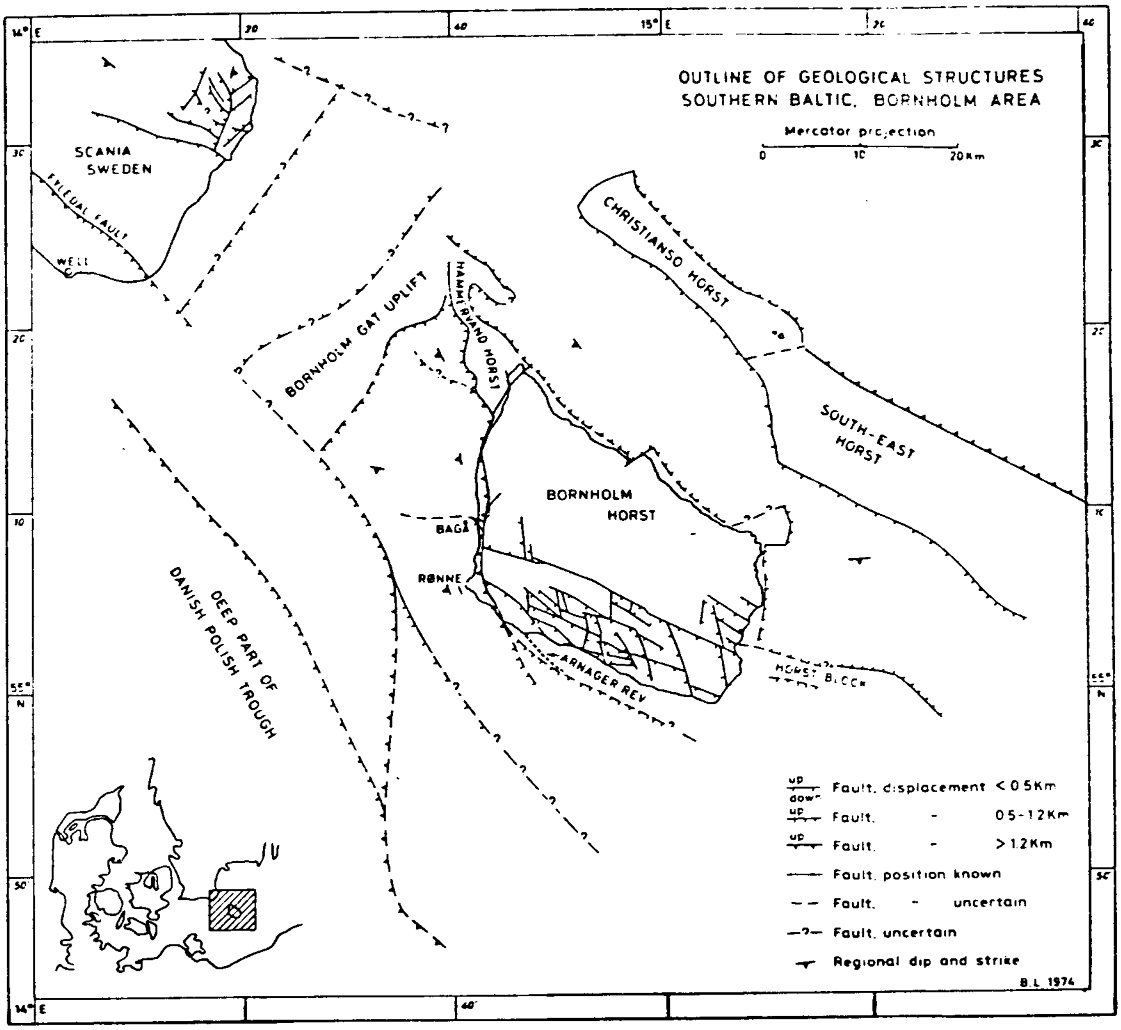



Fig. 21. Section from the mouth of the stream Vellensaa (SW) to Robbedale (NE), Arnager-Sose Fault block (from Gry 1960)



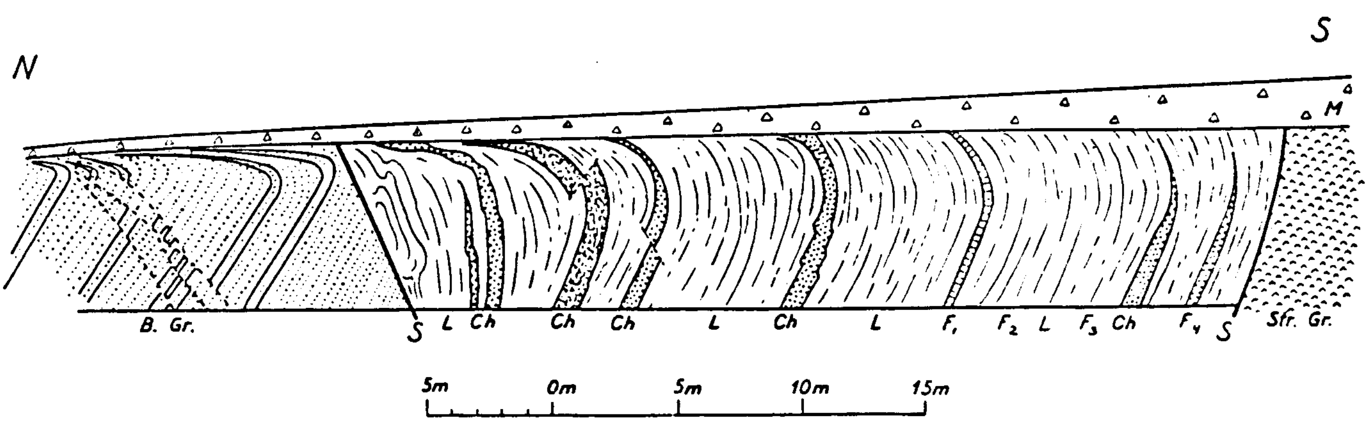

Profil af lagene ved Risebæks munding. D = 'Dicellograptus Skifer', T = 'Tretaspis Skifer', KL = Keuperler, KS = Keupersand og konglomerat. M = moræne. Pilen peger mod bækløbets bund.

Fig. 22. Section from the mouth of the stream Risebæk (from Gry 1977a). The Lower Palaeozoic strata comprises the uppermost 5 m of the *Dicellograptus* Shale (D) and the lower part of the Jerrestad Formation (T) *(Tretaspis* Shale). The Triassic Risebæk Member (KL and KS) is down faulted along a normal fault which strike E-W.




*Major geological structures in the Baltic around Bornholm. The indicated fault displacements are on the surface of the basement and do not necessarily continue through the whole sedimentary section.*

Fig. 23. Major geological structures in the Baltic around Bornholm (from Andersen et al. 1975).




Section at Jydegaard, Knudsker, Bornholm.
Str. G. = Striated granite, chloritized. L = Jydegaard formation, clay. Ch = Chamosite-oolite, gravel, sand and clay-ironstone. $F_1$ = clay-ironstone, fossiliferous. $F_2$-$F_4$ = fossiliferous horizons. B. Gr. = Bavnodde greensand. S = fault. M = boulder clay.

Fig. 24. Section of the Jydegård Formation and Bavnodde Greensand from the Jydegård clay pit, Knudsker (from Gry 1960).

# III EXCURSION LOCALITIES

GEOLOGICAL MAP OF BORNHOLM - PRE-QUATERNARY DEPOSITS

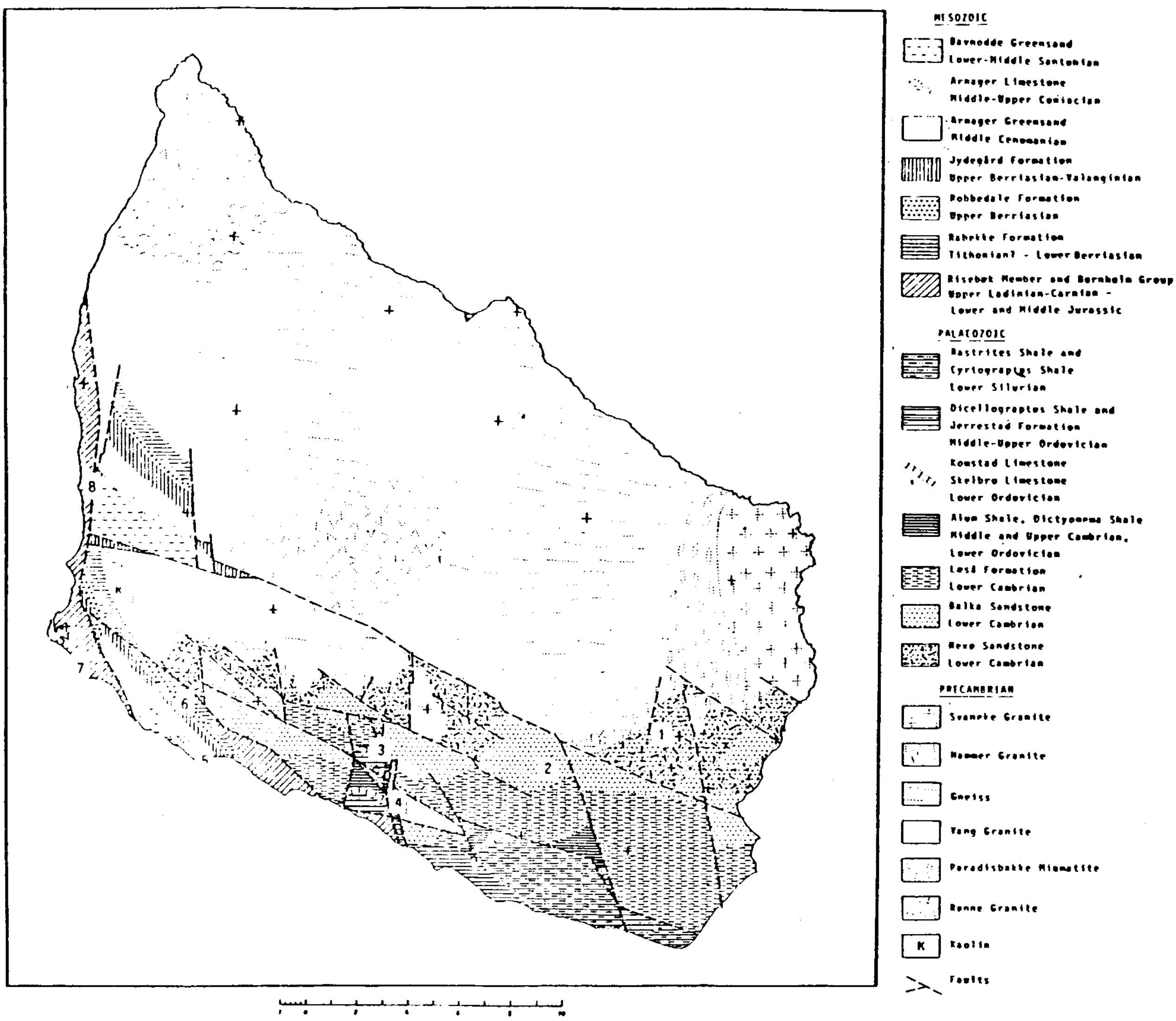



Fig. 25. The position of the excursion localities are indicated by letters on the map. 1. Gadeby, 2. Pedersker, 3a-3c. Læså, 4. Limensgade (described by *Merete Bjerreskov*) and 5. Arnager, 6. Robbedale, 7. Galgeløkke, 8. Bagå (described by *Peter Gravesen*).

## LOCALITY 1 - GADEBY

*Lower Cambrian Nexø Sandstone*

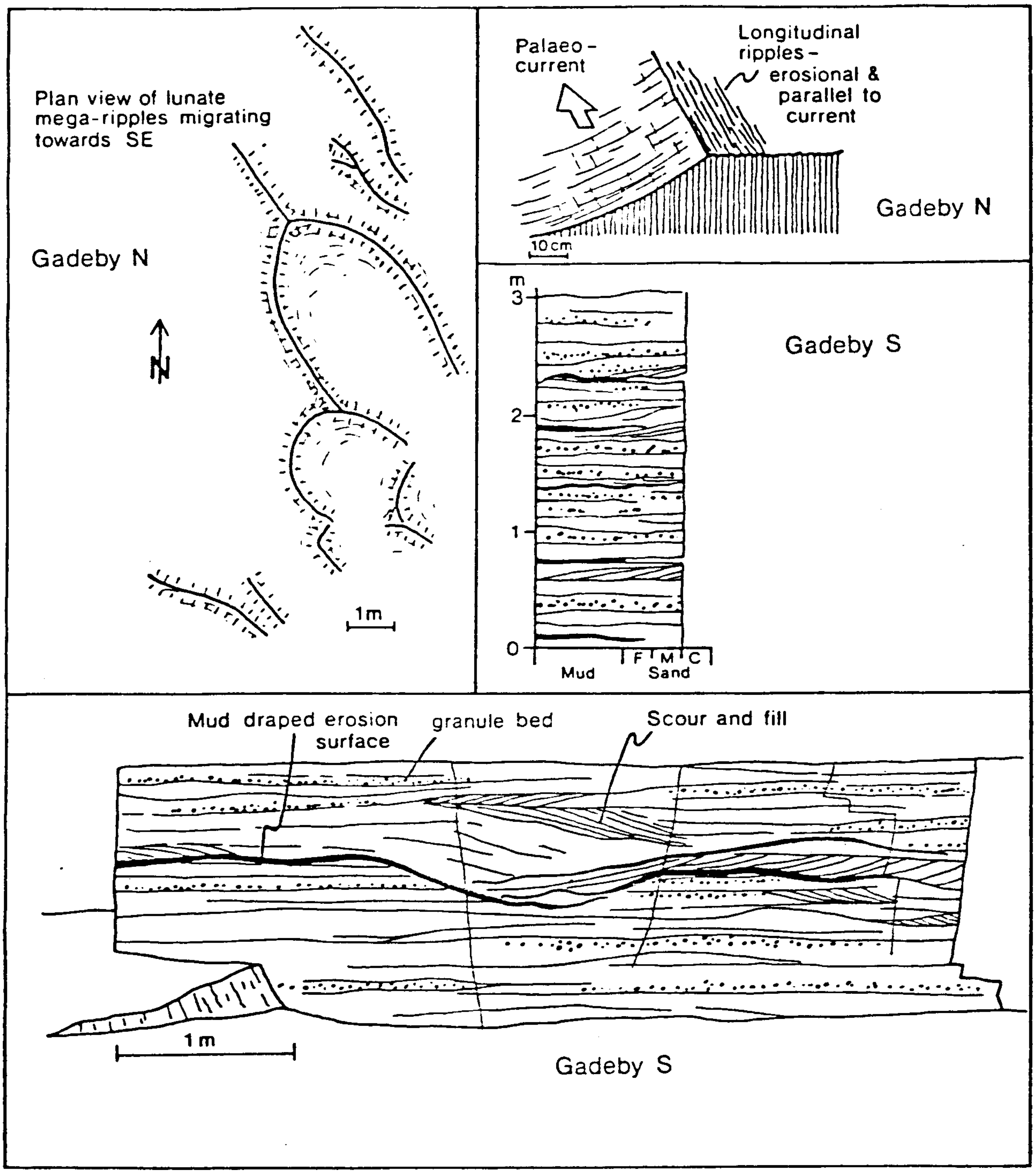
The two quarries at Gadeby expose section from the lower part of the 100 m thick Nexø Sandstone (Fig. 5). The sequence rests unconformably on the weathered Precambrian basement and consists mainly of red sandstone, coloured by hematite and generally with a feldspar content of 10-20%. Thin beds of greenish micaceous sand and siltstone separate the 50-100 cm thick sandstone layers. Sediment structures comprise lunate mega-ripples, scour and fill structures, planar lamination, desiccation cracks and load structures (Fig. 26). The Nexø Sandstone has been partly kaolinized by secondary processes. No fossils have been observed.

Surlyk (1980) suggested that the sand was deposited in a featureless floodplain with rapid deposition alternating with desiccation. The transport direction is generally to the S-SSE. Evidence from the opaque minerals shows that the sand comes from a source region outside Bornholm, possibly from Sweden (Jensen 1977).

The transition to the overlying Balka Sandstone is gradual and the upper parts of the Nexø Sandstone include some glauconite layers (cannot be observed in Gadeby).

Glacial striae with an approximate E-W direction can be observed on the surface of the sandstone.

*Geological age.* The Nexø Sandstone was previously regarded as being of Eocambrian age (e.g. Hansen 1936) since no fossils have been recorded. According to better knowledge of Tommotian faunas however, V. Poulsen (1978) suggested that the formation is not much older than the Balka Sandstone and corresponds to the lower part of the Tommotian Stage. The two formations might be regarded as members of the Scanian Hardeberga Sandstone Formation (Bergström & Ahlberg 1981, V. Poulsen 1978).




Details of the Lower Cambrian fluviatile Nekso Sandstone Formation.

Fig. 26. Details of the Lower Cambrian fluviatile Nexø Sandstone, Gadeby (from Surlyk 1980).

## LOCALITY 2 - PEDERSKER OLD QUARRY

*Lower Cambrian Balka Sandstone*

The old quarry north of Pedersker exposes a 4 m thick section from the middle part of the 60 m thick Balka Sandstone (Fig. 5).

In the quarry dark grey quartzarenitic sandstone is mainly found, alternating with generally thin beds of dark grey mudstone. A few conglomerate beds with well rounded quartz pebbles and some beds with rip up clasts of dark mudstone are also present.

Several mega-ripples show that the current direction was from east to west. Planar lamination and wave ripples are present. The bedding planes are transected by stylolitic seams and sineous trace fossils occur on the surface of one megaripple. The Balka Sandstone was deposited in a tidally influenced near shore marine environment (Surlyk 1980).

*Geological Age.* The Balka Sandstone Formation is regarded as Lower Cambrian. The lower part of the formation is glauconitic, indicating the Early Cambrian transgression. Vertical burrows (*Skolithos*, *Monocraterion* and *Diplocraterion*) are present, but no body fossils are found. V. Poulsen (1978) included the Balka Sandstone into the Scanian Hardeberga Formation.

## LOCALITY 3 - LÆSÅ STREAM BETWEEN KALBY AND VASEGÅRD

The 1.5 km long section shows profiles *(loc. 3a-3c)* in stream-cuts from the Lower Cambrian to the Upper Ordovician (Figs. 5, 27). The strata are generally inclined about $5^{o}$ to SSE.

## LOCALITY 3A - KALBY

The stream-cut represents formations from the late Lower Cambrian to Upper Cambrian.

*Lower Cambrian Broens Odde Member ("Green Shales")*

The stratigrafically lowermost part of the profile (upstream) shows the upper layers of the 100 m thick "Green Shales" (Fig. 5, 29).

The sequence consists mainly of glauconitic siltstone, occasionally sandstone, and in the middle part (not exposed here), a large number of phosphorite nodules are present. The siltstone is generally highly bioturbated, and flaser and lenticular laminated. In the upper layers at this locality, several sandy beds are present, and the "Green Shales" grades into the overlying Rispebjerg Sandstone (Fig. 29).

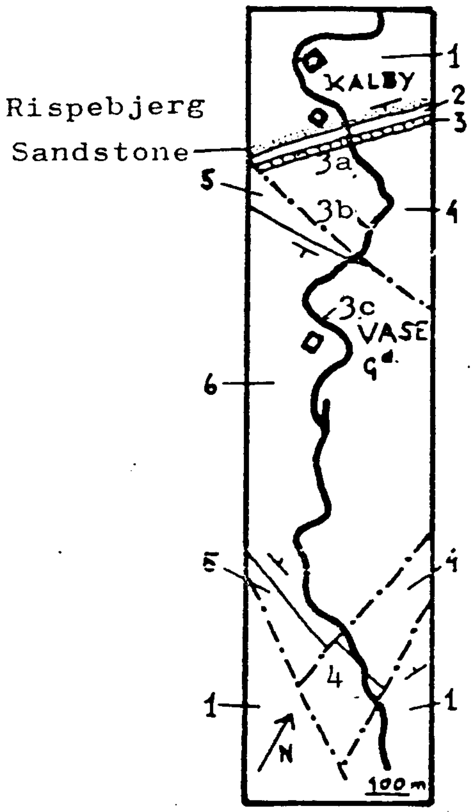
In the phosphorite nodules the fossil content comprise a diverse fauna (about 30 species) with sponges, hyolitids and molluscs (C. Poulsen, 1967).

*Lower Cambrian Rispebjerg Sandstone*

The 3 m thick light, grey Rispebjerg Sandstone is a calcitic/siliceous quartzarenite, with well rounded quartz grains, occasionally glauconitic. The sandstone layers are intercalated with phosphatized calcium carbonate. Bioturbation has been intense, and *Cruziana* trails have been observed (C. Poulsen 1967). On the surface the numerous brown spots possibly indicate weathered pyrite grains. The upper 40 cm is thoroughly impregnated by phosphorite.

*Geological age.* The fossils in the "Green Shales" indicate the Lower Cambrian *Schmidtiellus mickwitzi* Zone (e.g. V. Poulsen 1968) and the Rispebjerg Sandstone is referred to the *Holmia?* Zone). The uppermost Lower Cambrian is not represented on Bornholm (hiatus).

Fig. 27.




Locality 3a-c Læså from Kalby to Vasegård
Locality 4 Limensgade
Cambrian to Ordovician

6: Tretaspis -and Dicellograptus Shales

5: Komstad and Skelbro Limestones

4: "Upper Alum Shale"

3: Andrarum Limestone

2: "Lower Alum Shale"

1: Læså Formation:

"Green Shales" & Rispəbjerg Sandstone

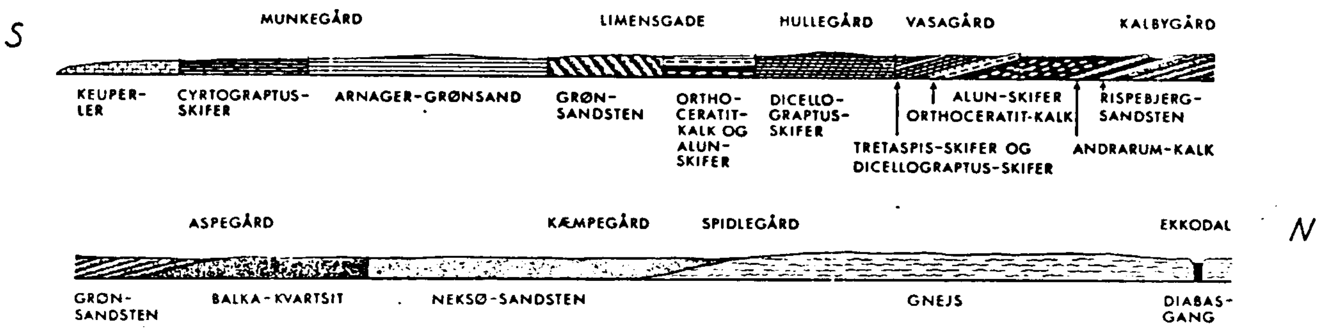



Fig. 28. Section along Læså (from Rasmussen 1966).

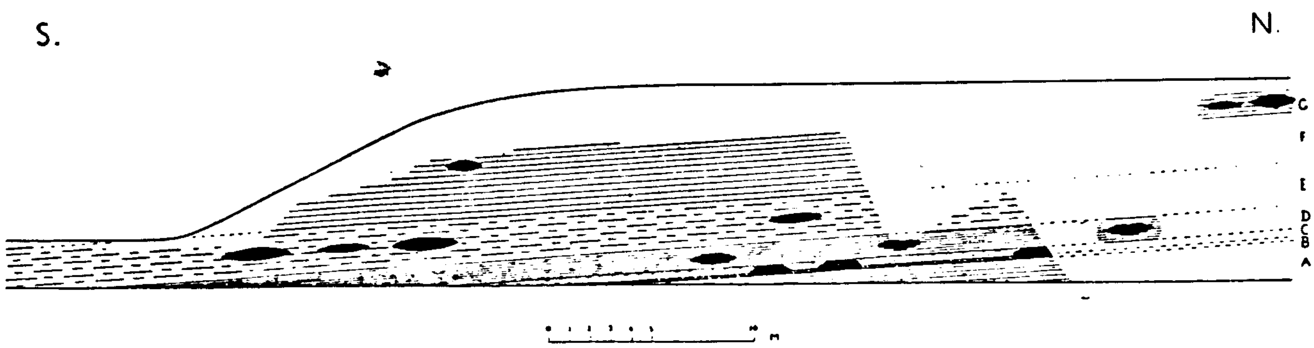



Fig. 6. Section in the Upper Cambrian at locality 6, Læsaa. A = *Orusia lenticularis* level, B = *Eurycare latum* level, C = *Eurycare angustatum* level, D = *Ctenopyge flagellifera* level, E = *Ctenopyge tumida* level, F = *Peltura scarabaeoides* level, G = *Parabolina longicornis* level. Black spots = Anthraconite lenses (from POULSEN).

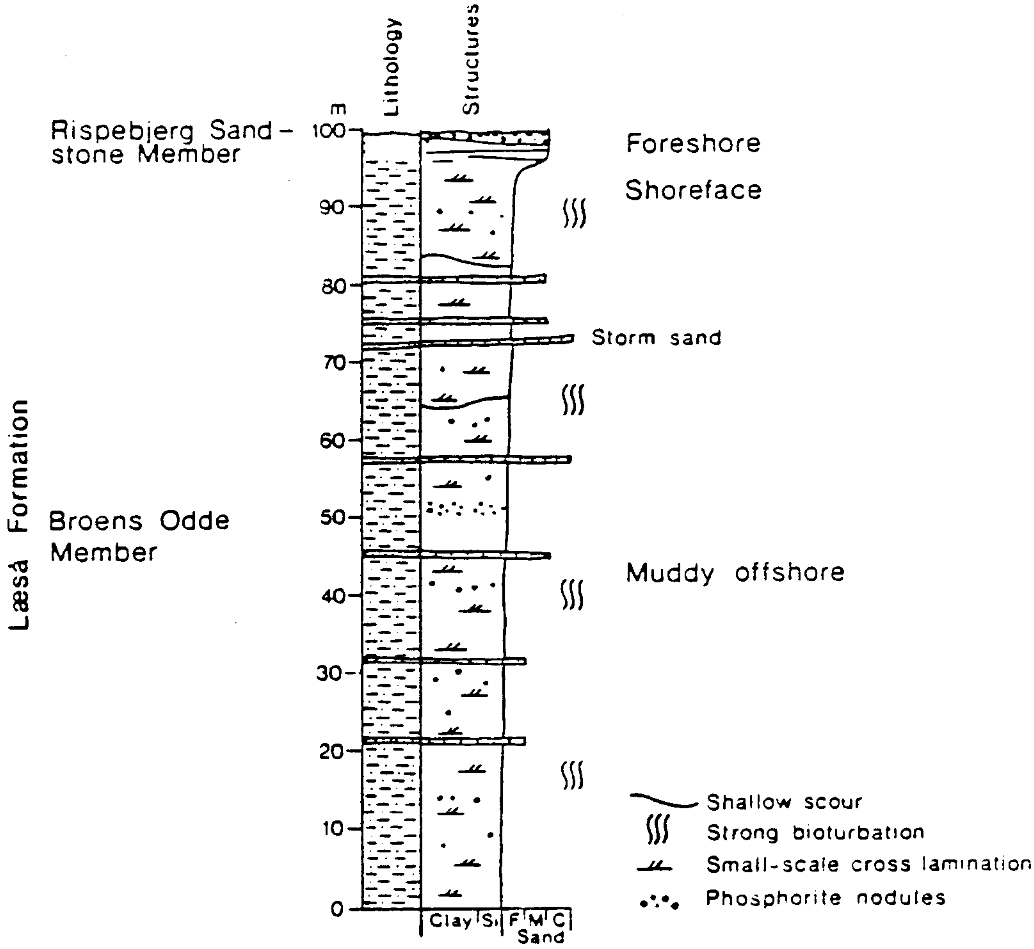
Fig. 28 a. Section of the Upper Cambrian deposits at locality 3 b (from C. Poulsen 1923).

Surlyk (1980) suggested that the "Green Shales" and Rispebjerg Sandstone should be included as members of the Læså Formation. He interpreted the Læså Formation as representing a prograding linear coastline. The environment was an off-shore shelf with the water depth just below mean wave base. The phosphorite nodules and the bioturbation indicate slow sedimentation with periods of non-deposition and occasionally occur storm sands. The Rispebjerg Sandstone was interpreted as deposited in a shoreface to foreshore environment and the well rounded grains suggest wave reworked aeolian sands. Marino (1980) suggested that the sand was deposited in a tidal complex on the landward side of a sandy barrier.

*Middle Cambrian Kalby Member*

The 15 cm thick Kalby Member overlies the phosphorite impregnated surface of the Rispebjerg Sandstone (Fig. 30), and is a light grey unconsolidated marl bed with an upper pyritic bed. The marl contains 35% calcite, a sandy portion with quartz grains, glauconite and phosphorite, a silty portion with mainly calcite grains and phosphoritized pebbles of the "Green Shales". The clay content is about 5%. The pyritic bed is max. 5 cm thick and consists of lumps of pyrite with more or less rounded clasts of phosphoritic and phosphatic sandstone. The transition to the overlying "Lower Alum Shale" is sharp. The diverse fauna in the Kalby Member comprises trilobites, hyolitids, inarticulate brachiopods and echinoderm fragments (Berg-Madsen, 1981).

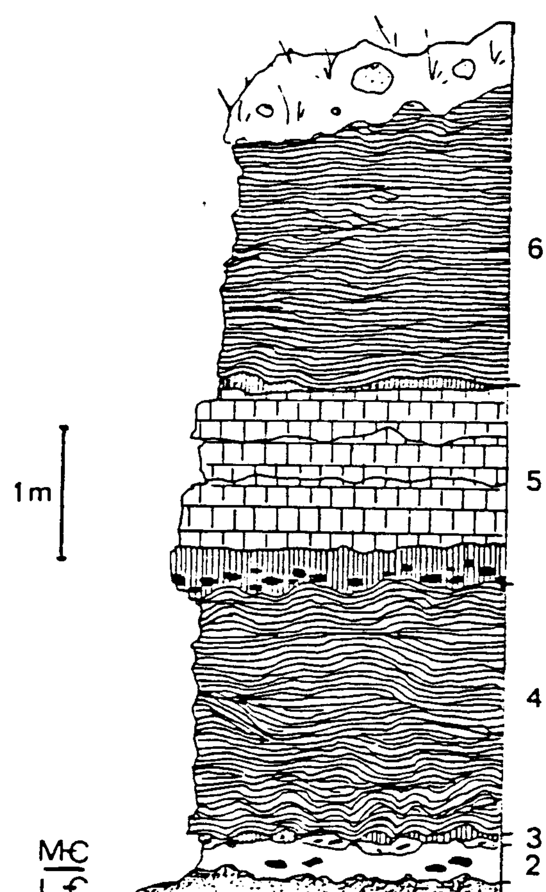
*Geological age.* The age of the Kalby Member (earlier Kalby Clay) has been discussed several times (Hansen 1937, C. Poulsen 1942, V. Poulsen 1963, and Berg-Madsen 1981). Berg-Madsen (1981) suggested that the Kalby Member is a part of the Exulans Limestone, and the marl bed was referred to the *Triplagnostus gibbus*-*Ptygagnostus atavus* Zones (the *Paradoxissimus* Stage), of the same age as the Borregård Member in the Exulans Limestone exposed in Øleå. It has been suggested that the Kalby Member is a weathering residue of a former limestone bed corresponding to the Borregård Member.




Coarsening-upwards sequence of the Læså Formation ( = « Green Shales » and Rispebjerg Sandstone Member).

Fig. 29. Section of the Læså Formation (from Surlyk 1980).

Fig. 30. Section of the Lower-Middle Cambrian transition at Læså (from Berg-Madsen 1981).




Sketch map of the exposure of Kalby Member at the Lower–Middle Cambrian transition and a profile of the sequence: (1) Rispebjerg Sandstone. (2) Kalby Member. (3) anthraconite. (4) 'Lower Alum Shale'. (5) Andrarum Limestone and anthraconite with phosphoritic conglomerate. and (6) 'Upper Alum Shale' below the glacial deposits. (Modified from V. Poulsen 1973.)

*Middle Cambrian "Lower Alum Shale"*

There is a break in sedimentation between the pyritic bed in the Kalby Member and the overlying Lower Alum Shale. This shale is a homogeneous black alum shale with thin anthraconite lenses at the bottom (Fig. 30).
The fossil content comprises rare trilobites.

*Geological age.* The trilobites indicate the *Hypagnostus parvifrons* - *Ptygagnostus punctuosus* Zones in the Middle Cambrian *Paradoxissimus* Stage (V. Poulsen 1966).

*The Middle Cambrian Andrarum Limestone*

The "Lower Alum Shale" is succeeded by a 20 cm fine-grained anthraconite bed of which the lower part is a conglomerate with phosphorite pebbles in an anthraconite matrix. The 85 cm thick Andrarum Limestone follows above the anthraconite beds (Fig. 30). It is a bituminous greyish black limestone with alternating dark and light coloured layers, limited by undulating bedding planes. Below the conglomerate, and above the Andrarum Limestone, half lenses of coarse-grained anthraconite concretions are found, up to 50 cm in diametre.

The Andrarum Limestone is highly fossiliferous with numerous fragments of trilobites, specially agnostids and paradoxidids.

*Geological age.* There is a break in sedimentation between the "Lower Alum Shale" and the phosphorite conglomerate underlying the Andrarum Limestone (V. Poulsen 1966). The phosphoritic conglomerate and the Andrarum Limestone are referred to the *Paradoxides forchammeri* Stage in the Upper Middle Cambrian.

*Middle Cambrian "Upper Alum Shale"*

The Andrarum Limestone is overlain by about 26 m of uniform black alum shale ranging in age from Middle Cambrian to Early Ordovician (Fig. 30).

The Middle Cambrian part of this shale is 2 m thick and the lowermost one metre is exposed in Kalby above the Andrarum Limestone.

*Geological age.* This part of the "Upper Alum Shale" is referred to the *Lejopyge laevigata* Zone (e.g. V. Poulsen 1966).

## LOCALITY 3B - LÆSÅ

*Upper Cambrian "Upper Alum Shale"*

A 50 m long and 8 m high profile in the upper part of the Upper Cambrian "Olenid Shales" is found here. The Upper Cambrian alum shale is 21 m thick and is a homogeneous black alum shale.

The shale contains abundant pyrite and well developed large lenses of anthraconite, more than 1 m in diametre and with very coarse-grained outer parts. There are numerous (up to 5 mm) long spindle shaped pyrite infilled pseudomorphoses from baryte (Callisen, 1914).

The fauna is dominated by olenid trilobites (C. Poulsen 1923), and on Bornholm the Upper Cambrian is divided into eight biozones. The trilobites remains are concentrated in thin beds in the shale and in the anthraconite lenses. Furthermore, brachiopods *(Orusia)* occur occasionally.

*Geological age.* The "Upper Alum Shale" is referred to the Upper Cambrian on the basis of olenid trilobites.

Passing further down the stream the uppermost part of the "Olenid Shale" with the large anthraconite lenses, is exposed in the bottom of the stream, and just south of a small bridge the succeeding Lower Ordovician *Dictyonema* Shale occurs. However, the 1 m thick exposure can be observed only at extreme low water level (von Janson 1979). East of the stream a small pond (an old quarry) exposes a 1 m high profile of the Ordovician Komstad Limestone.

## LOCALITY 3C - VASEGARD

*Middle-Upper Ordovician Dicellograptus Shale*

Further down the Læså stream a long profile exposes the uppermost 2/3rd of the approximately 12 m thick *Dicellograptus* Shale.

The *Dicellograptus* Shale is a very dark grey claystone and contains few fossils in the lower part of the profile, incl.

biserial graptolites, inarticulate brachiopods (e.g. *Paterula*) and few gastropods. Some bentonite beds occur in the profile generally 1-2 cm thick, one 10 cm thick.

*Geological age.* In the profile the Upper Llandeilian *Diplograptus multidens* and the Caradocian *Dicranograptus clingani* and *Pleurograptus linearis* Zones are represented (Hadding 1914 and Bergström & Nilsson 1974). Specially rich graptolite horizons are observed in the *clingani* Zone in the middle part of the long profile.

The *Dicellograptus* Shale has no proposed formal lithostratigraphic name. Jaanusson (1963) established the Vasegård Stage for the *P. linearis* Zone at Vasegård.

*Upper Ordovician Jerrestad Formation ("Tretaspis Shale")*

The southern part of the long profile, at the farm yard Vasegård, exposes the overlying Jerrestad Formation ("Tretaspis Shale").

The lower boundary of the Jerrestad Formation is indicated by a 40-50 cm thick mudstone layer, very rich in pyrite concretions (specially in the lower part), and appearing as a yellowish band due to strong weathering. Above this zone follows 40 cm of bioturbated grey green mudstone with a few brachiopods. The overlying sequence is a grey mudstone, brownly weathering, with trilobite fragments. Two limestone beds (3 cm and 7 cm thick) can be observed. The exposed part of the Jerrestad Formation is about 3 m thick here.

*Geological age.* The "*Tretaspis* Shale" - the Jerrestad Formation established by Jaanusson (1963) - on Bornholm is referred to the upper part of the Ashgillian *Eodindymene pulchra* and *Staurocephalus clavifrons* Zones. The pyritized horison possibly represents the transition Vasegårdian-Jerrestadian Stages (? sedimentation break) (V. Poulsen 1966).

LOCALITY 4 - LIMENSGADE

*Lower Ordovician Dictyonema Shale*

The lower part of the profile in the old quarry at Limensgade exposes the Lower Ordovician continuation of the alum shale facies - the *Dictyonema* Shale. The Cambrian-Ordovician transition is on Bornholm only indicated by the incoming of *Dictyonema flabelliforme sociale*, 3.90 m below the Skelbro Limestone (von Janson 1979).

The *Dictyonema* Shale is similar to the Upper Cambrian alum shale, rich in pyrite but devoid of anthraconite concretions. The fossils in the *Dictyonema* Shale include representatives of *Dictyonema* and the brachiopod *Broeggeria salteri*. The upper part (58 cm) of the shale was named the *Clonograptus* Shale (C. Poulsen 1922), and consists of dark to medium grey claystone with small anthraconite, pyrite and phosphorite concretions. *Clonograptus*, *Adelograptus* and *Bryograptus* rarely occur.

Just below the overlying limestone a 1-5 cm thick horizon comprises claystone impregnated with phosphorite. Few conodonts are observed.

*Geological age.* The *Dictyonema* Shale has no formal lithostratigraphic name. The sequence is referred to the Tremadocian, comprising the zones *D. flebelliform sociale - Bryograptus kjerulfi* von Janson (1979).

*Lower Ordovician Skelbro Limestone and Komstad Limestone*

Between the *Dictyonema* Shale and the Skelbro Limestone there is a considerable hiatus comprising the main part of the *Ceratopyge* Shale, the *Ceratopyge* Limestone and the Lower *Didymograptus* Shale. The Skelbro Limestone is 40 cm thick. The lowermost part (12-15 cm) consists of a conglomerate with numerous pebbles of phosphorite impregnated shale in a glauconitic limestone matrix, and is delimited upwards by an bored omission surface. The Skelbro Limestone is light grey biomicrite with numerous phosphatic pebbles and several omission surfaces.

The overlying 4.5 m thick Komstad Limestone, of which 2.5 m is exposed, is separated by an omission surface (hiatus ?) from the Skelbro Limestone. The Komstad Limestone is a dark grey biomicrite with thick carbonate beds separated by thin layers of mudstone or by omission surfaces.

Both the Skelbro and Komstad Limestone have a diverse fauna of randomly orientated (due to bioturbation) trilobites together with orthocone cephalopods, gastropods and brachiopods.

*Geological age*. The Skelbro Limestone comprises the *Cyclopyge stigmata* Zone in the *Didymograptus hirundo* Zone and is referred to Arenigian (V. Poulsen 1965). The Skelbro Limestone was separatec by a hiatus from the Komstad Limestone, which was referred to the *Asaphus expansus* - *Asaphus lepidures* zones (e.g. V. Poulsen 1966). The Skelbro and Komstad Limestones are being revised (persn. comn. A.T. Nielsen, 1982).

In the bottom of the Læså stream north of the old quarry the transition Komstad Limestone-*Dicellograptus* Shale can be observec at low water level. A 30 cm thick phosphorite conglomerate is succeeded by 1.5 m alternating dark grey mudstone and light grey metabentonite (the latter is not exposed). The transition includes a considerable hiatus, comprising the Llandvirnian Upper *Didymograptus* Shale and the lower part of the Llandeilian.

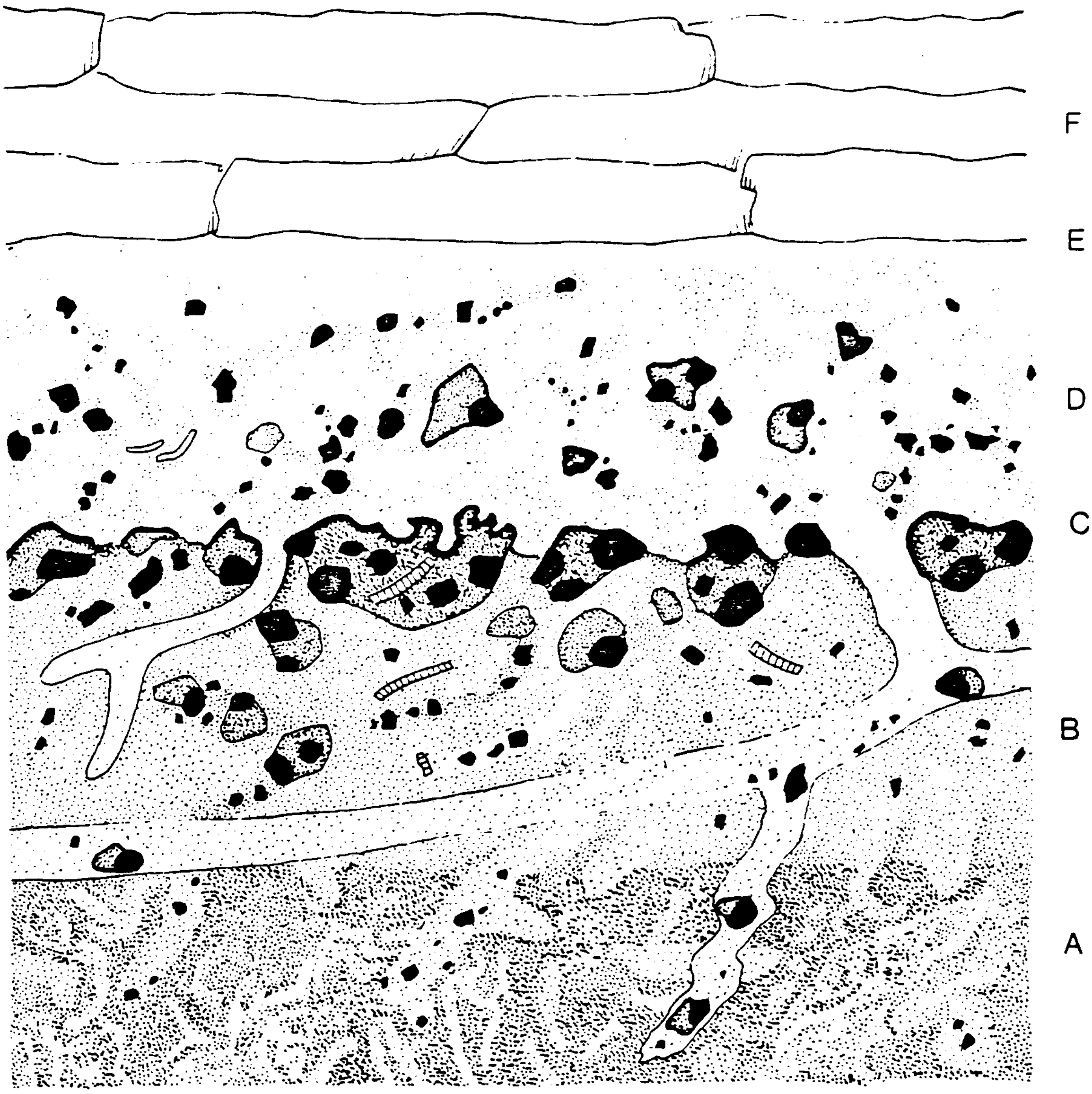
## LOCALITY 5 - ARNAGER

*The Middle Cenomanian Arnager Greensand and Middle-Upper Coniacian Arnager Limestone*

The locality is a cliff situated west of the town, Arnager, on the south coast of Bornholm (Fig. 25):

The uppermost part of the Arnager Greensand is exposed in the eastern part of the cliff. It consists of loose glauconitic quartz sand, which is strongly bioturbated. Light coloured burrows *(Thalassinoides)* with bifurcations probably produced by crustacerean can be followed downwards from the overlying bottom bed of the Arnager Limestone. The burrows are filled by sand containing Cenomanian to Coniacian foraminifera (Stenestad 1972). In the sediments are found a relatively diverse fauna of ammonites, belemnites, bivalves, gastropods, brachiopods, coccoliths and foraminifera (Ravn 1916, Douglas & Rankin 1969, Hart 1979, Forchheimer 1970, Kennedy, Hancock & Christensen 1980).

The Arnager Greensand is unconformably overlain by the Arnager Limestone. This formation starts with a 20 cm thick horizon of richly glauconitic limestone, which contains compound phosphoritic and glauconitised, unfossiliferous intraclasts and a hardground recently described in detail by Bromley (1979) (see text to Fig. 31). The overlying calcilutitic limestone, which is thinly bedded, has only about 50-60% calciumcarbonate, and the rest comprises fine-grained quartz sand, clay and silicous matter. The silica originates mainly from sponge spicules, which can be recognized as needle shaped impressions in the limestone. The limestone is rather hard, compacted and lithified. The lower part of the limestone is light coloured: white or white yellow, while the upper part is blue grey because of a higher content of clay (Christensen 1977). Silicified horizons of the limestone are intensely bioturbated, but well-defined *Thalassinoides* is common. A fauna of ammonites, belemnites, brachiopods, echinoids, asteroids, corals and foraminifera is registered from the formation (Ravn 1918, Dougles & Rankin 1969, Stenestad 1972, Christensen 1973).




Lithology of the bottom bed of the Arnager Limestone, overlying the Arnager Greensand. A: Arnager Greensand, a highly bioturbated greensand, richly glauconitic, containing no phosphatic clasts except those piped down from the overlying beds by burrowers. Top junction not very sharp. B: richly glauconitic limestone, the basal bed of the Arnager Limestone, containing dark brown, phosphatized clasts of a limestone less rich in glauconite grains than the surrounding matrix (clasts indicated in black). Chiefly towards the top of unit B, these clasts are incorporated within compound intraclasts of richly glauconitic limestone. Sediment (with clasts) of unit B is extensively piped down into the topmost levels of Unit A within numerous burrows. C: sharp junction tinted dark green with impregnated glauconite; the impregnation most strongly affects the compound intraclasts where these are in contact with the junction. Although encrusting organisms and organic borings are not in evidence, this glauconitised surface is clearly a hardground. D: fairly hard limestone, pale grey, containing irregularly distributed glauconite grains together with phosphatic and compound intraclasts, chiefly in burrow fills. From the base, large *Thalassinoides suevicus* up to 8 cm in diameter, and much smaller *T. paradoxicus* penetrate the underlying unit B. Some of the *T. suevicus* continue down into the uppermost metre of unit A. E: well defined parting plane. F: slabby, hard Arnager Limestone of normal lithofacies, almost free of glauconite grains.

Fig. 31. Details of the topbeds of the Cenomanian Arnager Greensand and the bottom beds of the Coniacian Arnager Limestone (from Bromley 1979).

The two formations dip a few degrees in a south-westernly direction because of the Laramide tectonic phase. The Arnager Limestone is cut by differently orientated joints systems.

*Geological age.* The Arnager Greensand is on basis of ammonites and foraminifera, dated to Early Middle Cenomanian (Hart 1979, Kennedy, Hancock & Christensen 1980). The Arnager Limestone was earlier referred to Upper Turonian (Ravn 1918, Birkelund 1957), mainly because of poorly preserved ammonites, bivalves and belemnites. The formation is now dated as Middle-Upper Coniacian from foraminifera and belemnites (Douglas & Rankin 1969, Stenestad 1972, Christensen 1973).

## LOCALITY 6 - ROBBEDALE

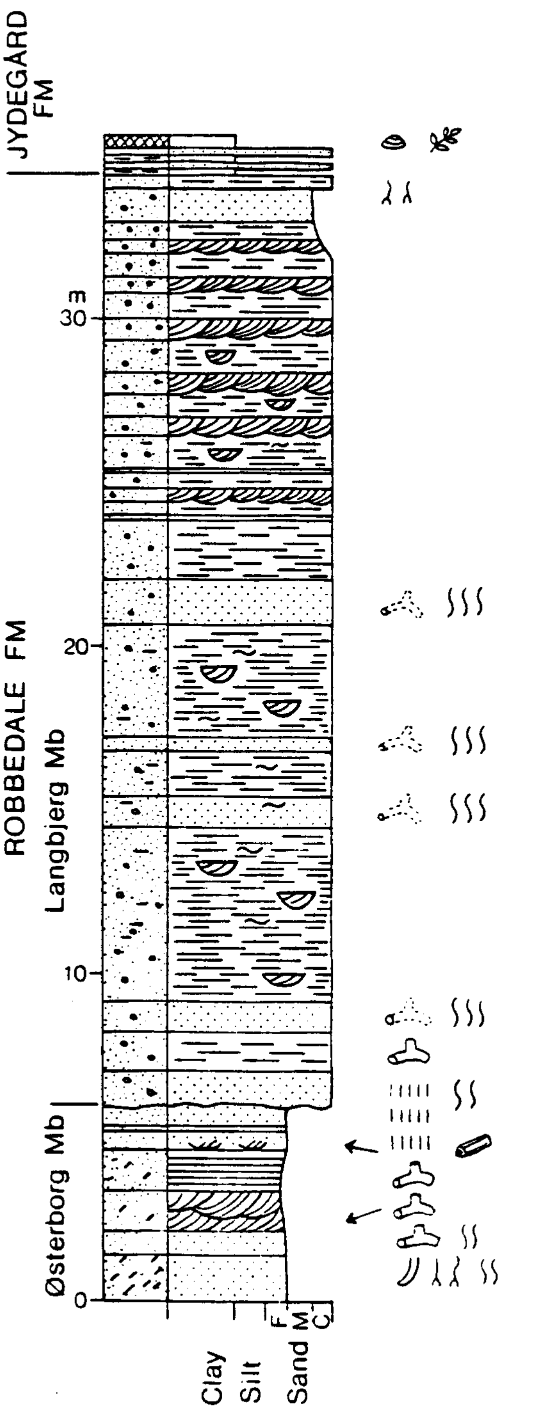
*The Upper Berriasian-Valanginian Robbedale and Jydegård Formations*

In the Robbedale area (Fig. 25) exists several sand pits, where sections from the Østerborg and Langbjerg Members of the Robbedale Formation and the Tornhøj Member of the Jydegård Formation are well exposed (Figs. 32, 33).

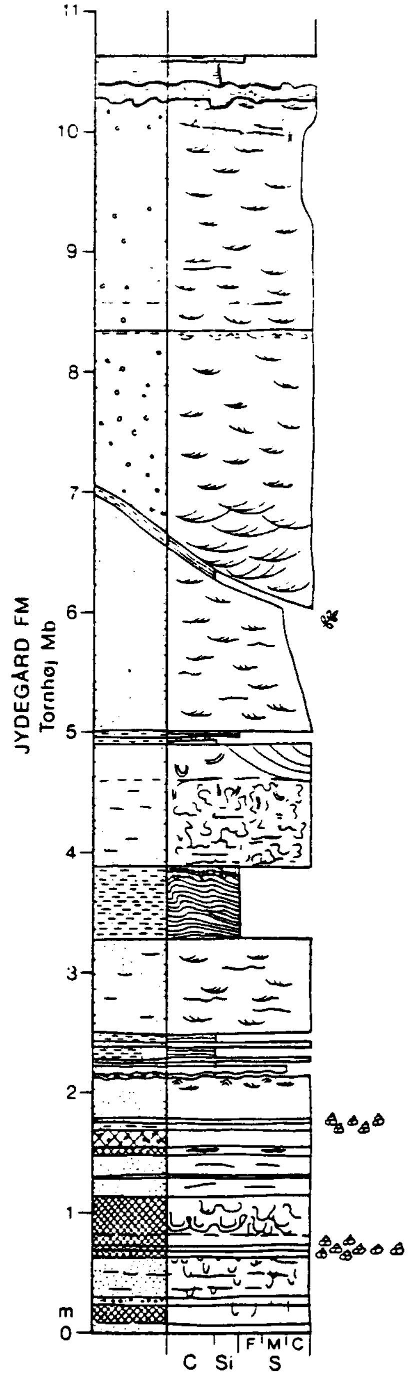
The lower Østerborg Member consists mainly of fine-grained quartz sand. It can be horizontally laminated, trough cross-bedded or structureless and is often totally bioturbated. Galleries of *Ophiomorpha* and *Skolithos* and other trace fossils are characteristic and beds with abundant plant detritus and rootlets are found (Fig. 32).

The sediments of the Østerborg Member are deposited along a linear shoreline in the upper shoreface, foreshore, and in small lagoons. The Østerborg Member is succeeded by the Langbjerg Member, and the boundary is sharp. The Langbjerg Member (Fig. 32) consists of coarse-grained faintly horizontally laminated and indistinctly trough cross-bedded quartz sand with many clay flasers. Strongly bioturbated beds with *Ophiomorpha* and other "*Ophiomorpha*"-like trace fossils are abundant and totally structureless sandbeds are found in the uppermost part (Fig. 32). The beds have a sheetlike geometry and can be followed over a large area outside the pits, e.g. from wells. The sediments represent a high-energy shoreline with deposition on the shoreface and foreshore beach of a barrier island complex.

The Langbjerg Member is conformably overlain by the Tornhøj Member of the Jydegård Formation (Fig. 32, 33). The member comprises alternating beds of horizontally laminated clay, strutureless clay-ironstone, silt and horizontally laminated and cross-bedded sand and sandstone. Load structures and trace fossils are found in few beds. In several horizons, concentrations of monispecific assemblies of fresh and brackish gastropods, bivalves and conchostracans (e.g. *Neomiodon* are *Viviparus*) are found. The bed geometry is sheetlike in the lower part (Fig. 33), while clay and sand filled channels are characteristic of the upper part. The Tornhøj Member is deposited in a large lagoonal-lacustrine system with lagoon, back-barries and washover fan sedi-




Type section of the Robbedale Formation at A/S Carl Nielsen's sand pit. Position indicated by 2 on fig. 7. Measured by P. Gravesen in 1977.




Reference section of the Jydegård Formation. Reference section of the Tornhøj Member. Position indicated with 2 on fig. 7. Measured by N. Noe-Nygaard and F. Surlyk in 1980.

Fig. 32. Section of the Lower Cretaceous Robbedale Formation, A/S Carl Nielsen's sand pit, Robbedale (from Gravesen et al. 1982).

Fig. 33. Section of the Lower Cretaceous Jydegård Formation, A/S Carl Nielsen's sand pit, Robbedale (from Gravesen et al. 1982).

ments situated behind the barrier beach deposits of the Langbjerg Member. The sediments of the formations have been studied by Gry (1956, 1960, 1968), Jux & Strauch (1968), and recently by Gravesen (1977, 1982) and Noe-Nygaard & Surlyk (in prep.).

*Geological age.* The age of the Robbedale Formation can only be determined indirectly as no age diagnostic fossils are found at present. The underlying Rabekke Formation contains ostracods, which according to Christensen (1974), are contemporareous with forms from the German Oberer Münder Mergel and Serpulit, which today is dated as Lower-Upper? Berriasian (Dörhöfer & Norris 1977, Surlyk 1980). The Jydegård Formation contains ostracods, which can be connected with forms from the German Wealden 3 (Christensen 1974) and this unit is now dated as Upper Berriasian to Valanginian. The Robbedale Formation is thus probably dated as Upper Berriasian.

## LOCALITY 7 - GALGELØKKEN

*The Sinemurian Galgeløkke Member of the Rønne Formation*

The locality, which is the type of locality for the Galgeløkke Member, is a low sea cliff situated just outside the town, Rønne (Fig. 25).

The section (Fig. 34) can be separated in three units. The lower unit, which is seen in the eastern part of the cliff, is dominated by tidal flat heteroliths of wavy, lenticular and flaser-laminated fine-grained sand and clay with water-escape structures and a low bioturbation of e.g. *Planolites*. The middle unit (Fig. 35) consists of medium- to coarse-grained large scale cross-bedded sand (often as herringbone cross-bedding showing a bimodality in the palaeocurrent), which is intercalated by thin beds of wavy and flaser-laminated sand and clay. The cross-bedded units is upbuilt of bundles with mud draped foresets and numerous reactivation surfaces (pause planes), and are interpreted as tidel channels deposits and shoal sands. Water-escape structures are found here also, and *Skolithos* is abundant, often forming right angles to the foresets. *Planolites* is rare.

The upper unit from the western part of the cliff is again dominated by lenticular and flaser-laminated tidal flat heteroliths with few *Planolites*. Beds of medium-grained large scale cross-bedded sand and small symmetric scours, intepreted as tidal creeks, also occur in this unit. A clay bed with rootlets overlain by an autochtonuous coal-seam of supratidal marsh origin is found on the top. This complex is probably formed during a depositional regression, which does not necessarily indicate a regional sea-level change. Recently, the sediments have been investigated by Rolle (1977) and Sellwood (1972, 1975).

The Laramide tectonic movements cause the member to dip approximately 10 degrees towards the southeast. An angular unconformity of approximately 2 degrees, which is found in the upper heterolithic unit, could also be of tectonic origin but probably reflects low-amplitude topographic relief in the tidal flat area (Gravesen et al. 1982).

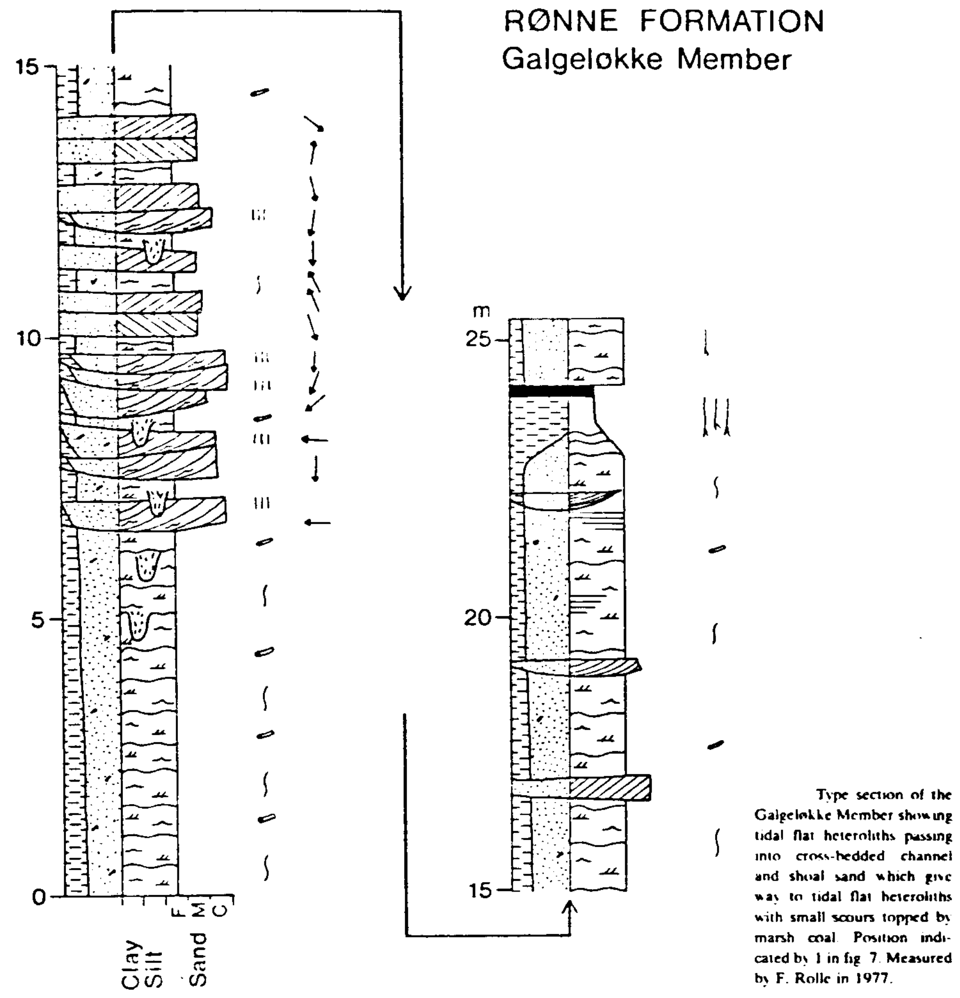
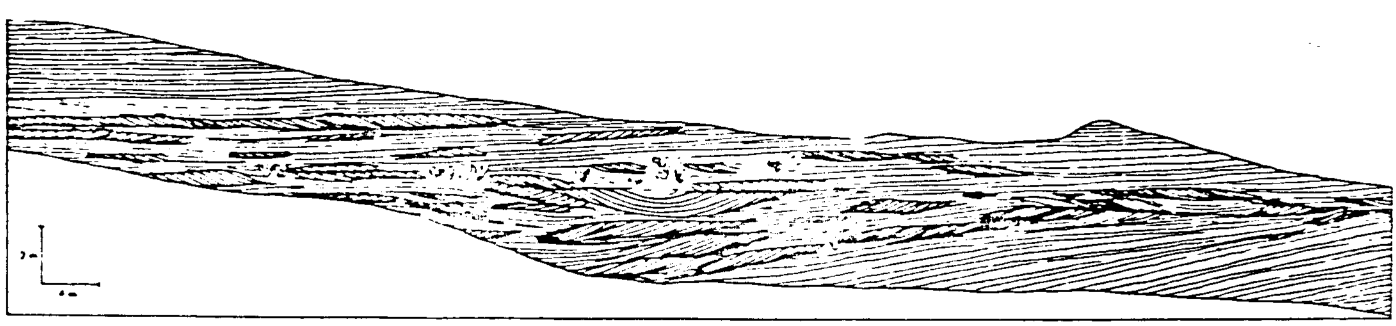



Fig. 34. Section of the Lower Jurassic Galgeløkke Member from the cliff Galgeløkken just east of Rønne (from Gravesen et al. 1982).



Profile through large tidal channel in the Sinemurian (?) sequence of Galgeløkken, SW Bornholm. The channel is filled with large-scale cross-bedded sand alternating with heteroliths. It is under- and overlain by sandy heteroliths of a mixed flat origin (after ROLLE 1978).

Fig. 35. Sedimentological details of the Galgeløkke Member (after Rolle 1978 published in Surlyk 1980).

*Geological age*. Sinemurian. The age can be determined indirectly on the basis of the stratigraphic position of the member between the underlying Sose Bugt Member of Lias *alpha* (Hettangian to lowermost Sinemurian) age, and the overlying Hasle Formation of Lias *gamma* (Lower Pliensbachian) age (Gry 1969, Gravesen et al. 1982).

## LOCALITY 8 - BAGÅ (HASLE KLINKERFABRIK CLAY PIT)

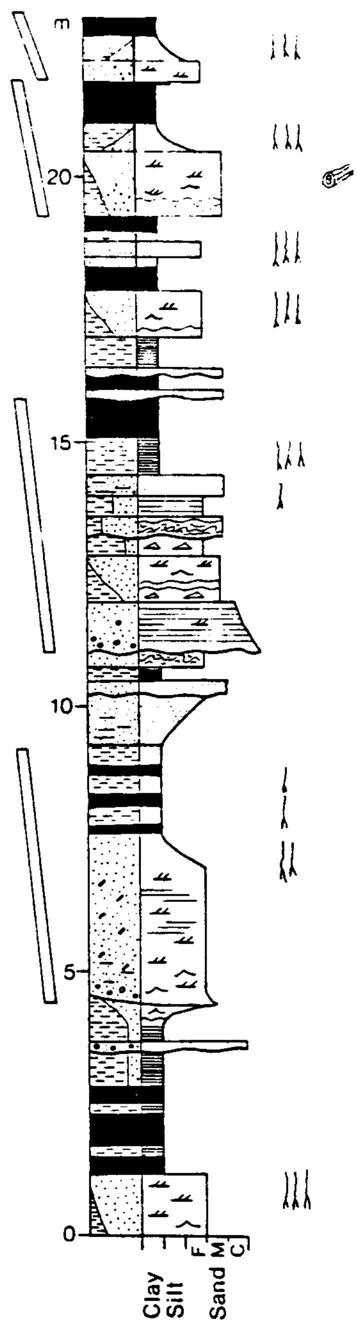
*The Bajocian-Bathonian Bagå Formation*

The locality Bagå is situated west of the town Muleby and west of the Hasle-Rønne fault line (Figs. 18, 25). In the area south of the Hasle Klinkerfabrik are sediments of the Bagå Formation exposed (Fig. 36). The type locality of the formation is found in the Hasle Klinkefabrik clay pit with a sequence of different sediment types. Gravel, cross-bedded fine and medium-grained sand, kaolinitic sandstone, heteroliths, clay-ironstone, laminated clay and coal-seams are characteristically arranged in fining-upwards cycles. Fine-grained carbonaceous detritus and rootlets are abundant, but are most commonly found in connection with the clay and the overlying autochthonous coal-seams. Plant fossils have been described by various authors (e.g. Bartholin 1892, 1894, Möller 1902, 1093, Florin 1958, Gry 1969). A freshwater bivalve is found in a clay bed (Gry 1969) and a medium-grained sand bed has been intensely bioturbated by *Diplocraterion* (Rolle et al. 1979). The mineralogy of the clay was investigated by Graff-Petersen & Bondam (1963) and the contents and amount of kaolin, illite, vermiculite, chlorite and mixed-layer clays indicate an "underclay" origin for most of the clay which was deposited in a flat swamp area in a deltaic environment.

The formation is consequently interpreted as having been deposited in a lower delta plain environment. The fining upwards sand-clay-coal-cycles were formed in a system of meandering channels, levees and back swamps. Marginal marine conditions are indicated by the marine trace fossils and brackish water beds (Gry 1969), and deposition of clay developed in interdistributary bays (Rolle et al. 1979, Gravesen et al. 1982).

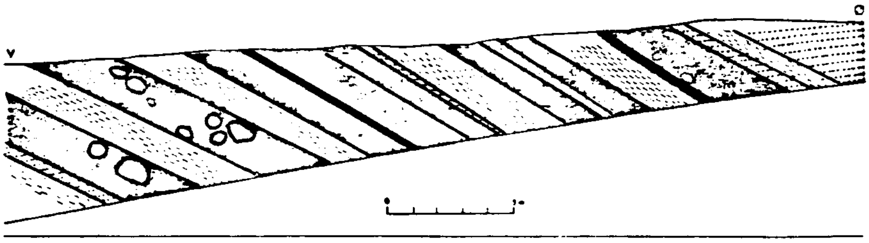
In the upper part of the formation are extremely poorly sorted conglomerates, which is exposed in the northeastern corner of the pit (Fig. 37). Beds of structureless poorly sorted sand and clay contain boulders of kaolinized granite more than 1 m in diametre. The conglomerates are produced by debris flows, which have slid into the depositional basin from the nearby fault scarp of a granite horst which is immediately to the east of the basin. At the fault the Jurassic were down thrown against the Precambrian rocks (Gry 1960). The formation has a strike between

BAGÅ FORMATION




Type section of the Bagå Formation. Hasle Klinkerfabrik clay pit. Position indicated by 1 in fig. 20 and 1 in fig. 23. Measured by F. Rolle in 1976

Fig. 36. Section of the Bagå Formation, Hasle Klinkerfabrik clay pit (from Gravesen et al. 1982).



Hasle Klinkerfabrik. Profil fra nedkørslen til lergraven med mudderstrømme med op til meterstore granitblokke. Set mod nord.

Fig. 37. Section through the Bagå Formation in the Hasle Klinkerfabrik clay pit showing the alternating beds of debriss flow conglomerates, sand, clay and coal (from Gry 1977b).

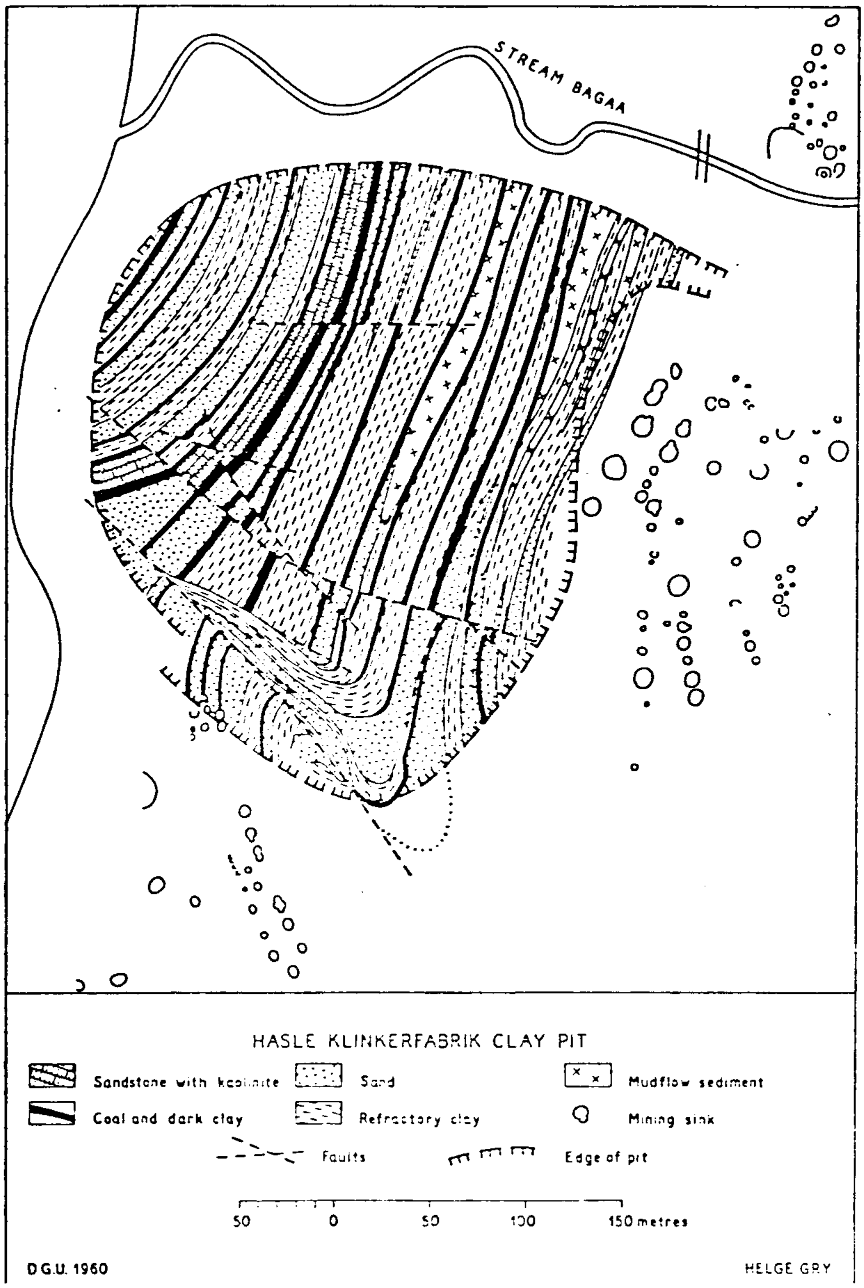



Fig. 38. Map of the Hasle Klinkerfabrik clay pit showing the distribution and tectonics of the Middle Jurassic Bagå Formation (from Gry 1960).

from 25-35° and dips 17-25° to southeast in the pit and the beds are cut by several faults (Fig. 38). These disturbances are related to the uplift of the area during the Laramide orogeny, where tectonic movements inverted the former sedimentary basins.

*Geological age.* The formation is dated as Middle Jurassic Bajocian-Bathonian. Florin (1958) studied the Bagå flora of taxads and conifers, which he related to the Middle Jurassic flora of Yorkshire and Gry (1969) investigated the megaspores and found forms described from the Bajocian-Bathonian Yorkshire Deltaic Series.

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# A P P E N D I X

## REVIEW OF DANISH REGIONAL GEOLOGY AND TECTONICS

BY

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APPENDIX

# REVIEW OF DANISH REGIONAL GEOLOGY AND TECTONICS

by

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## INTRODUCTION

This report is a review of pre-Quaternary geological and structural evolution of the Danish area as it can be interpreted from well data, seismic data, and outcrops. It has been compiled from published interpretations, completed by observations not yet published.

An overall review of the geological and structural setting of the Danish area in the Northwest European realm is given in Ziegler (1978).

For the use of formation and member names and of stratigraphical definitions we refer the following papers:

1) Concerning Mesozoic: Bertelsen (1978 and 1980), Michelsen (1978a), Stenestad (1972), Larsen (1966).
2) Concerning the Cretaceous-Tertiary boundary a comprehensive volume were edited by Birkelund & Bromley (1979).
3) Preliminary onshore mapping of Palaeogene formations was published by Dinesen et al. (1977).

Well data are in abbreviated form published by Sorgenfrei & Buch (1964), Rasmussen (1974 & 1978), Michelsen (1976), and Well Data Summary Sheets, Vol. 1-3. 1981-1982 (Danm. geol. Unders.). Regional seismic mapping in the Fennoscandian Border Zone is published by Baartman & Christensen (1975). A map showing the structural outline of Denmark by Baartman is published in Rasmussen (1978) and is included in the present guide-book.

## 1. STRUCTURAL FRAMEWORK

The subsurface structural framework of Denmark including the Danish sector of the North Sea may be subdivided into the following major elements.

*The Fennoscandian Border Zone*, forming the northern termination of the Tronquist-Teisseyre Lineament, separates the stable Precambrian and Palaeozoic Fennoscandian Craton from the NW-European Basins. It is a complex block fault zone with a documented history going back into the Late Carboniferous-Early Permian times with several later reactivations during the Kimmerian and Laramide tectonic events.

The Fennoscandian Border Zone stretches from northernmost Jylland southeastwards through Kattegat and Scania into the southern Baltic Sea. The island of Bornholm is a horst structure located in the Fennoscandian Border Zone separated from Scania by giant fault zones delimitating the Rønne Graben filled with Mesozoic sediments.

*The Ringkøbing-Fyn High* and the Møn Block is a Hercynian trend of highs lining up westwards with the Mid North Sea High in the British part of the North Sea. This system of structural highs separates the *Norwegian-Danish Basin* to the north and the *North German Basin* to the south.

The Ringkøbing-Fyn High is transected by the Horn Graben in the North Sea area and a number of minor troughs in the onshore area.

The Ringkøbing-Fyn High is separated from the Mid North Sea by the *Central Graben* part of the Mesozoic North Sea rift system. The Dogger High (located in westernmost part of the Danish North Sea) is the most southerly of a chain of narrow and elongated mid-graben highs.

## 2. CRYSTALLINE BASEMENT

Crystalline basement rocks are only exposed on the island of Bornholm. These rocks can be subdivided into a group of early orogenic granitic gneisses (Svecofennian ?) and a group of anatectic and intrusive postorogenic granites giving K/Ar mineral ages of approximately 1340 M.Y. (Larsen 1971). These granites correlate with similar anorogenic granites in Blekinge on the south coast of Sweden.

Crystalline basement has been reached in few onshore wells along the crestal part of the Ringkøbing-Fyn High and in the Fennoscandian Border Zone (northernmost Jylland). K/Ar determinations on material from Fyn and Jylland give ages of 800-900

M.Y. similar to ages obtained in southern Norway and southwestern Sweden. It is unknown whether these rocks have been formed during the Dalslandian orogenic cycle or the ages reflect a Dalslandian overprinting of older Svecofennian rocks.

Greenschists of Caledonian age (420 M.Y.) have been penetrated on Dogger High. Similar ages have been obtained on low grade metamorphic rocks from wells in northernmost Germany. This suggests the existence of a branch of the Caledonian system linked with the Scottish-Norwegian Caledonides to extend from the Central Graben area, running south of the Ringkøbing-Fyn High and joining the Late Silurian fold belt under the Polish Trough (Ziegler 1978)

## 3. PALAEOZOIC

### *Cambro-Silurian*

Cambro-Silurian sediments are exposed in a system of slightly tilted WNW trending fault blocks on the southern part of Bornholm. The Precambrian basement is overlain by about 100 m of Eocambrian continental arkosic sandstones, succeeded by 60 m Early Cambrian marine sandstones and 100 m glauconitic siltstones. This sequence is in turn overlain by 120 m of predominantly dark marine shales ranging in age from Middle Cambrian to Middle Silurian.

Well data on Early Palaeozoic rocks are scarce elsewhere in Danmark. A section of about 350 m sandstone and shales ranging in age from Early Cambrian to Early Silurian with a major Ordovician hiatus has been drilled on the upthrown side of a tilted fault-block on Sjælland (Poulsen 1974). Approximately 300 m of tilted Late Silurian clastic sediments and basaltic volcanics have been drilled in Jylland (Christensen 1971).

Seismic data indicate a thick unfolded Early Palaeozoic rock pile in Skagerrak, northern Jylland, and the Kattegat area. On Sjælland there is seismic evidence of a system of predominantly N-S trending tilted fault blocks below the Base Zechstein reflector, locally with several kilometres thick Palaeozoic rocks preserved.

*Devon-Carboniferous*

During Devonian and Carboniferous times the major parts of Denmark were a positive area and probably acted as a source of clastic supply to the sedimentary basins to the south and southwest.

On the northern flank of the Dogger High, an about 50 m thick Late Visean - Namurian sequence is drilled. The sediments are of a marginal, fluvial dominated facies with intercalations of platform limestone (cf. Bertelsen 1978). They are overlying 18 m non-dated red-beds on top of the Caledonian greenschists.

On the island of Falster, south of the Møn Block, more than a 500 m thick Early - Middle Visean series of platform limestones, partly in paralic facies, is drilled (cf. Michelsen 1971 and Bertelsen 1972).

The presence of Late Carboniferous is not yet stated with certainty.

*Permian*

Strike-slip movements took place along the Tornquist-Teisseyre Lineament in Late Carboniferous-Early Permian times associated with intrusion of a NW-SE dyke swarm in Scania. The Oslo Graben with highly alkaline volcanics located at the northern termination of the Tornquist-Teisseyre Lineament may be considered as a pull-apart feature at the termination of a transcurrent fault (Ziegler 1978). The Horn Graben, crossing the Hercynian trending Mid North Sea- Ringkøbing-Fyn Møn High, is of the same age and shows the same trends as the Oslo Graben. The margins of the High are characterized by rather gentle slopes and minor faults.

Mildly alkaline, bimodal volcanics of this age have been drilled along the flanks of Ringkøbing-Fyn High and in Horn Graben (Dixon et al. 1980). On both sides of this trend of highs red beds of presumably Rotliegendes age have been deposited, but due to limited well control the actual geometry of the northern Rotliegendes sedimentary basin is poorly known in the Danish area.

At the onset of Zechstein times a sea way extended from the Arctic Permian Basins southwards through the area of the future Norwegian-Greenland Sea and northern North Sea into the NW European Zechstein Basins separated by Mid North Sea High - Ringkøbing-Fyn High. The extension of Zechstein north of Ringkøbing-Fyn High marks the geometry of the future Danish- Norwegian Basin, which started to subside as part of the northern Zechstein basin during this period.

The Zechstein transgression led to deposition of thin deep water carbonates and laminated anhydrites in the basinal areas and thick shallow water carbonate and anhydrite banks at the basin margins and local highs. Arid climate, restricted influx of sea water and periodic eustatic sea level changes led to infilling of the two basins with the cyclical Zechstein evaporite series.

In southern Jylland along the margin of the southern Zechstein basin carbonate-anhydrite facies prevailed (Sorgenfrei & Buch 1964, Clark & Tallbacka 1980), grading into predominantly halite facies to the south.

In the central part of the Norwegian-Danish Basin evaporites in excess of 1000 m were deposited. The Zechstein lithostratigraphy have been established from well data in salt diapirs in North Jylland showing correlation with the development in Germany (Jacobsen 1971). So far only 3 cycles have been demonstrated in Northern Jylland, two of them with potassium precipitation.

Halokinetic movements of the Zechstein rock salt started during Keuper times and locally continues into the present. The correlation of the Zechstein depositional cycles in the two basins indicate free communication presumably across the Mid North Sea High and along the Central Graben. Halokinetic structures both in the northern and southern part of the Danish sector of Central Graben suggest that the Central Graben started subsiding during Zechstein times leading to halite deposition (Day et al. 1980), but major rifting did first take place in the Mesozoic associated with break up of the Pangean Megacontinent.

## 4. TRIASSIC - EARLY CRETACEOUS

*Triassic*

The structural framework created during the Late Palaeozoic made up the fundament for the Triassic sedimentation. The Ringkøbing-Fyn High was transsected by a few troughs and truncated by the Central Graben rift zone.

There is a difference in structural and sedimentary development of the area of the Central and Horn Grabens and the remaining part of the Danish area. In the latter considerable subsidence took place in the North German Basin and the Danish Subbasin of the Norwegian-Danish Basin where up to 6000 m Triassic sediments were deposited. As in Permian time the Ringkøbing-Fyn High has probably been elevated in Early and Middle Buntsandstein, and the two basins may have been connected via small troughs only. Except for the block west of the Horn Graben and for the Stevns Block the High was buried in Late Buntsandstein and remained subsided until the Mid Kimmerian tectonic event. Until the Keuper the Fennoscandian Border Zone was a positive region with restricted sedimentation. In Keuper the blocks north of the Fjerritslev Fault and Grenå-Hälsingborg Fault were overstepped and relative thick Keuper and Rhaetic sedimentary series were laid down north of here. At the same time halokinesis started centrally in the Danish Subbasin due to Triassic overbunden. Therefore, the local thickness of the Late Triassic, Jurassic, Cretaceous, and Tertiary sediments are radically changing within the Subbasin.

During the entire Traissic the source area has been to the north and northeast, and the depo-center was mainly located southwest of the Fjerritslev Fault. The Skagerrak Formation is found along the Border Zone and is time equivalent with the main part of the Triassic Formations to the south. It is a coarse-grained, arkosic sandstone probably deposited by alluvial fans along the faults limiting the Subbasin. In the remaining regions continental sediments are interbedded by brackish and marine sediments.

The Bunter Claystone and Sandstone Formations consist of braided river deposits. On the High and to the south clay is dominating, and north of the High the sediments become more coarse-grained and grade into the Skagerrak Formation. The Röt claystone (Ørslev Formation) interbedded with limestone and anhydrite were deposited under shallow marine-brackish conditions. In Muschelkalk marine conditions prevailed in the south (Falster Formation). The Early Keuper sediments (Tønder Formation) resemble those of the Middle Buntsandstein and represent a regressive period. In the Middle Keuper a new transgressive period started with deposition of claystone and siltstone (Oddesund Formation). The maximum transgression occured in the Late Keuper and grey claystone and limestone, partly dolomitic and oolitic (Vinding Formation) were deposited centrally in the Danish Subbasin. The reactivated block faulting in the Early Kimmerian phase accentuated the positive elements from where clastics were shed into the basin. Subsequently the marginal depositional zone (the fluvio-deltaic Gassum Formation) withdraw into the Fennoscandian Border Zone during Late Rhaetic and Early Jurassic. The depo-center moved northeastwards.

In the Central and Horn Grabens the Rhaetic is missing and the sedimentation is correlatable with that known from the southern North Sea (see Rhys 1974). The thickness is unknown, but exceeds 3000 m in southern Horn Graben, which acted as a rapid subsiding half-graben. In southern Central Graben approximately 1500 m Traissic sediments have been drilled.

*Jurassic*

Structurally the Jurassic is characterized by periodical block faulting in the Fennoscandian Border Zone and successive transgressions of this zone. Subsidence of the Danish Subbasin continues after the Triassic period, and a more than 1200 m thick sedimentary series was deposited. The Horn Graben was only slightly active, whereas the Central Graben was strongly subsided with deposition of more than 4000 m sediments (cf. Michelsen 1978b).

At the beginning of the Early Jurassic the first extensive Mesozoic transgrsssion took place. In the Danish Subbasin a shelf deposition of more than 900 m marine claystone (the

Fjerritslev Formation) was deposited. Coinciding with deposition of the lower part of the Fjerritslev Formation centrally in the Subbasin the fluvio-deltaic deposition (the Gassum Formation) continued northeast of the Fjerritslev Fault as well as in Scania. In Early Pliensbachian the main transgression took place into the Fennoscandian Border Zone (Michelsen 1975). At the end of the Early Jurassic the Subbasin was characterized by a slower subsiding rate, and lagoonal conditions prevailed centrally.

The Mid Kimmerian phase elevated the basinal regions southwest of the Border Zone and reactivated the block faulting in the Zone with associated volcanic activity in Scania.

Southwards the erosion due to the elevation has cut into the Fjerritslev Formation. On the Ringkøbing-Fyn High and south of it the Formation is totally missing. The erosion even has cut into the Late Triassic on the crestal part of the High. In the Central Graben only the lower part of the Early Jurassic is preserved, and in a sedimentary facies comparable to the Fjerritslev Formation.

The reoccurring block faulting in the Border Zone created a source area for fluvio-deltaic sedimentation (Haldager Sand) covering the Danish Subbasin as a sheet sand. Elevation of the Central Graben and the westernmost block of the Ringkøbing-Fyn High separated the northern and southern basinal regions and sourced corresponding sand layers interbedded with distinct coal beds into the Central Graben.

At the transition to Late Jurassic the delta plains were drowned. In the Subbasin interbedded claystone and siltstone series interpreted as tidal flat deposits were deposited. In the Central Graben claystone was deposited under probably anaerobic conditions. Subsequently extensive subsidence took place, especially in the Central Graben, where the so-called Kimmeridge Clay in a deep water facies was deposited. It is a thick claystone series rich in organic material.

Late Jurassic subsidence did also take place in the Danish Subbasin, where marine claystone of shelf facies (the Børglum Member) was deposited. Shallow marine or near shore arenaceous sediments (the Frederikshavn Member) comprise the Jurassic-Cretaceous boundary and probably reflect a minor accentuation of the Border Zone. The Late Kimmerian tectonic event coincided with an eustatic sea-level drop, but did not create any pronounced unconformity in the basinal area.

In the Central Graben an extensive hiatus is found close to or comprising the Jurassic-Cretaceous boundary caused by the Late Kimmerian event.

*Early Cretaceous*

Shelf sedimentation of marine claystone took place in the Central Graben, and in the Danish Subbasin successively after the shallow marine conditions mentioned above. The rate of subsidence has slowed down, the basins were filled in, and in the later part of the Early Cretaceous the Danish area became covered by the sea. Greyish marine claystone covers the Ringkøbing-Fyn High (at least partly) and the southern part of the area as well. Also on Bornholm the Early Cretaceous oversteps positive areas (cf. Gry 1960).

At the end of the Early Cretaceous the sediments changed character and became more calcareous. Reddish brown marlstone (the Rødby Formation) were deposited, except for the northern part of Jylland (e.g. the Border Zone) where greenish, glauconite rich sediments are found.

## 5. LATE CRETACEOUS - TERTIARY

Sedimentation of the Late Cretaceous limestone without clastic influx covered the entire area as a result of a global sea level rise. The main structural elements in the Danish area were partly covered up. A depo-center with sediment thicknesses greater than 1500 m is found in a regional NW-SE trending zone south of the Fjerritslev Fault and the Grenå-Hälsingborg Fault trending into the Danish-Polish Trough. The zone northeast of this trend, characterized by thick Jurassic series, has been inverted during Late Cretaceous - Early Tertiary. The Grenå-Hälsingborg Fault in Kattegat is interpreted as an upthrust of tangential compressive nature with Late Cretaceous missing northeast of it, partly due to erosion. Features within the flexure in the Border Zone, between Helsingør and Hälsingborg, indicate repeated pre-Senonian, Senonian, and Danian-Maastrichtian tectonic pulses (cf. Larsen et al. 1968).

The fault activity along the Central Graben has nearly stopped and the maximum thickness of Late Cretaceous limestone in the Graben is less than 1000 m. Laramide inversion did also take place in the southern Central Graben.

*Tertiary*

With the opening of the Greenland-Norwegian Sea at the Paleocene-Eocene transition the entire North Sea Basin started to subside in a saucer-shaped pattern with maximum subsidence rate along the former Mesozoic Grabens. The maximum thickness of the Danish Tertiary series exceeds 3000 m in Central Graben.

The sedimentation of white limestone continued in Danian time, with a few sedimentation stops, and in the eastern region with bioherms as a characteristic feature. At the end of the Danian the sedimentation canged to marl and claystone.

In Palaeogene the sedimentation of marine claystone was only interrupted by the volcanic ash layers at the transition Paleocene-Eocene. The Neogene sedimentation became more arenaceous. During the entire Tertiary the coast line retreated westwards in the onshore section of Denmark.

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During the 8th working meeting in Sweden and Denmark of Project Tornquist-Southwest border of the East-European Platform (IGCP project No. 86) an excursion in Bornholm took place, and on that occasion this guide book was prepared.

The geology and tectonic evolution of Bornholm is broadly outlined, and on the eight excursion localities the lithology and sedimentary structures of the deposits are described. The geological age of the sediments at each locality is mentioned.

In an appendix a review of the Danish regional geology and tectonics is presented.



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