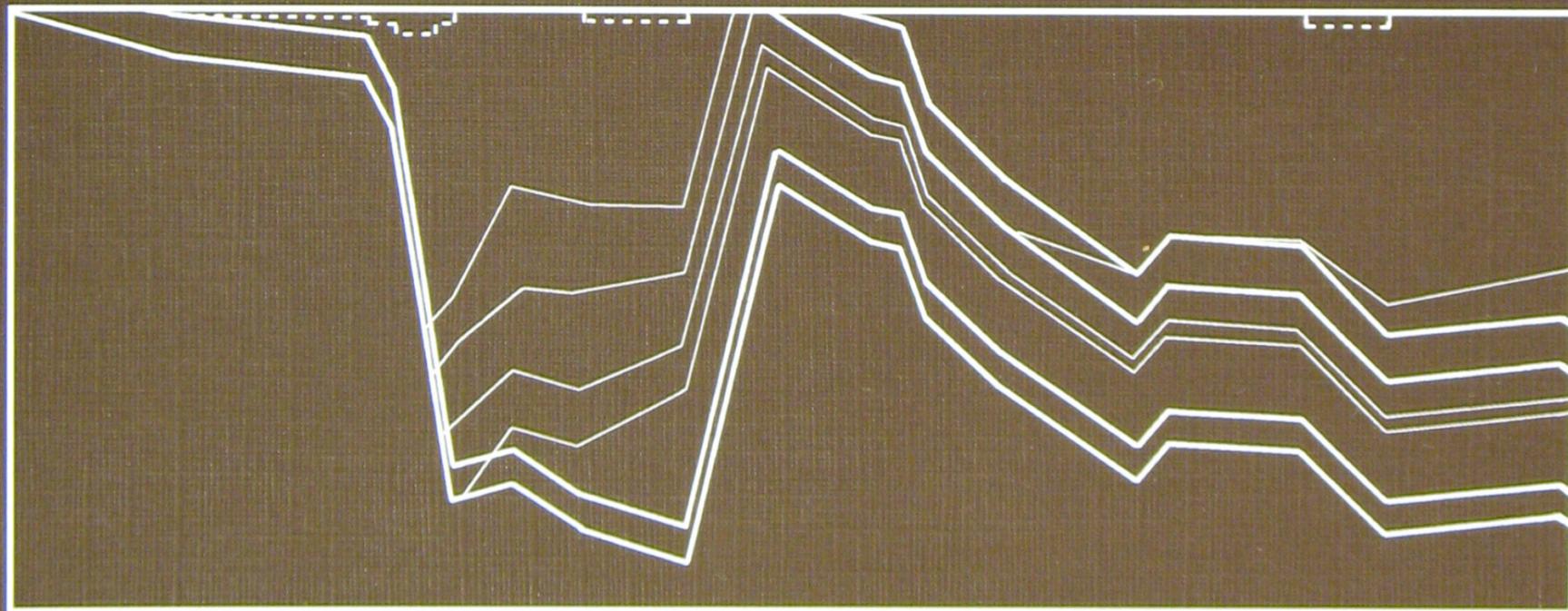


# Palaeozoic tectonic and sedimentary evolution and hydrocarbon prospectivity in the Bornholm area

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OLE VALDEMAR VEJBÆK, SVEND STOUGE AND KURT DAMTOFT POULSEN



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*Key words:*

Baltic Shield, Bornholm, Caledonian, Denmark,  
hydrocarbons, Paleozoic, Peribaltic Syncline,  
Seismic stratigraphy, stratigraphy, Tectonics.

With 4 plates

*Vignette:*

Extract from figure 10 showing the subsidence history at  
the location of the Pernille-1 well in the Rønne Graben.

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# Abstract

The present distribution of Palaeozoic sediments in the Bornholm area is a consequence of several different tectonic regimes during the Phanerozoic eon. This development may be divided into three main evolutionary phases:

**A Caledonian to Variscian phase encompassing the Lower Palaeozoic sediments. The sediments are assumed originally to have showed a gradual thickness increase towards the Caledonian Deformation Front located to the south. This pre-rift development may be further subdivided into three sub-phases:**

*A period of slow sedimentation on a relatively stable platform as recorded by the uniformly low thicknesses of the Cambrian to Lower Silurian sediments.*

*A period of foreland-type rapid sedimentation commencing in the Llandoveryan to Wenlockian, continuing in the Ludlovian and possibly into the Devonian. The period is characterized by folding and uplift of the Caledonides to the south causing tectonic loading of the foreland and resultant rapid sedimentation in the foreland basin.*

*A period of gravitational collapse causing minor erosion during the Devonian. The transition to the second major phase in the Phanerozoic structural development, during which the Sorgenfrei - Tornquist zone came into existence, is recorded by regional deposition of Carboniferous sediments. These sediments are, however, mostly removed by later erosion.*

**A syn-rift phase characterized by sedimentation in graben areas and expanding basins commencing in the Rotliegendes and continuing through the Triassic, Jurassic and Lower Cretaceous. This phase was probably initiated by a Late Carboniferous- Early Permian tensional dominated right-lateral wrench fault system within the Sorgenfrei-Tornquist zone.**

**A Post-rift development phase dominated by Late Cretaceous carbonate sedimentation. During Late Cretaceous and Early Tertiary times the Bornholm area was strongly affected by inversion tectonism caused by compressional strike-slip movements. This resulted in reverse faulting and uplift and erosion of former basinal areas.**

Understanding the two latter phases is important for understanding the present distribution of the Palaeozoic.

A key to understanding the hydrocarbon potential of the area is the maturation of the organic matter in the main potential source, the Ordovician Upper Alum Shale. Maturity was mainly achieved during the Silurian to Late Palaeozoic time, and little further maturation took place later. The Upper Alum Shale is accordingly expected to be overmature in the main part of the study area and mature in the Hanö Bay Basin. This reflects the assumed primary uniform thickness of the Lower Palaeozoic, with a general thinning towards the northeast.

COMPANY	OPERATOR	YEAR	QUALITY	Km.
DUC	WGC	1694	poor	184
OPAB	Various	1970-73	fair-poor	773
DUC	GSI	1975-76	good-moderate	2453
-	-	Reprocessed by Nopec 1992*	good-moderate	-
WGC	WGC	1982*	good	787
DUC	Geco	1983*	very good	193
WGC	WGC	1985*	very good	1034
Gexco	Geco	1986*	good	530
Norsk HYDRO	CGG	1986-87*	very good	1426
SECAB	Delft GBV	1987*	very good	469
JEBCO	Digital/Digicon	1988*	vert good	1648
AMOCO	PGI	1988*	moderate	160

Table 1: List of seismic surveys used in this study (\* = data not used in previously published studies).

# Introduction

The general objective of the study is to provide a synthesis of the Palaeozoic tectonic and stratigraphic development of the Bornholm area. A secondary objective is to outline the generalized hydrocarbon potential with respect to the Lower Palaeozoic succession of the area. The study is based on seismic interpretation supported by maturity modelling and analysis of well data from Pernille-1 drilled by Norsk Hydro in the Rønne Graben, and Stina-1 drilled by AMOCO in the Kolobrzeg Graben (see plates; Fig. 1).

Large parts of the original Palaeozoic basin infill have been removed by later erosion. The bulk of the remaining Palaeozoic sediments is preserved mainly in downfaulted

positions, and show major angular unconformable relationship to the overlying Permian and younger deposits. The Palaeozoic basin geometry is to a large extent obscured by more or less severe Mesozoic tectonism. Previous attempts to unravel the complex Phanerozoic structural development in the Bornholm offshore have been published by Vejbæk (1984, 1985). These attempts were however hampered by the absence of the now available well control. Further insight has also been gained from reprocessing the seismic data available at that time as well as the acquisition of further infill data. This study used all available released seismic data (Table 1).

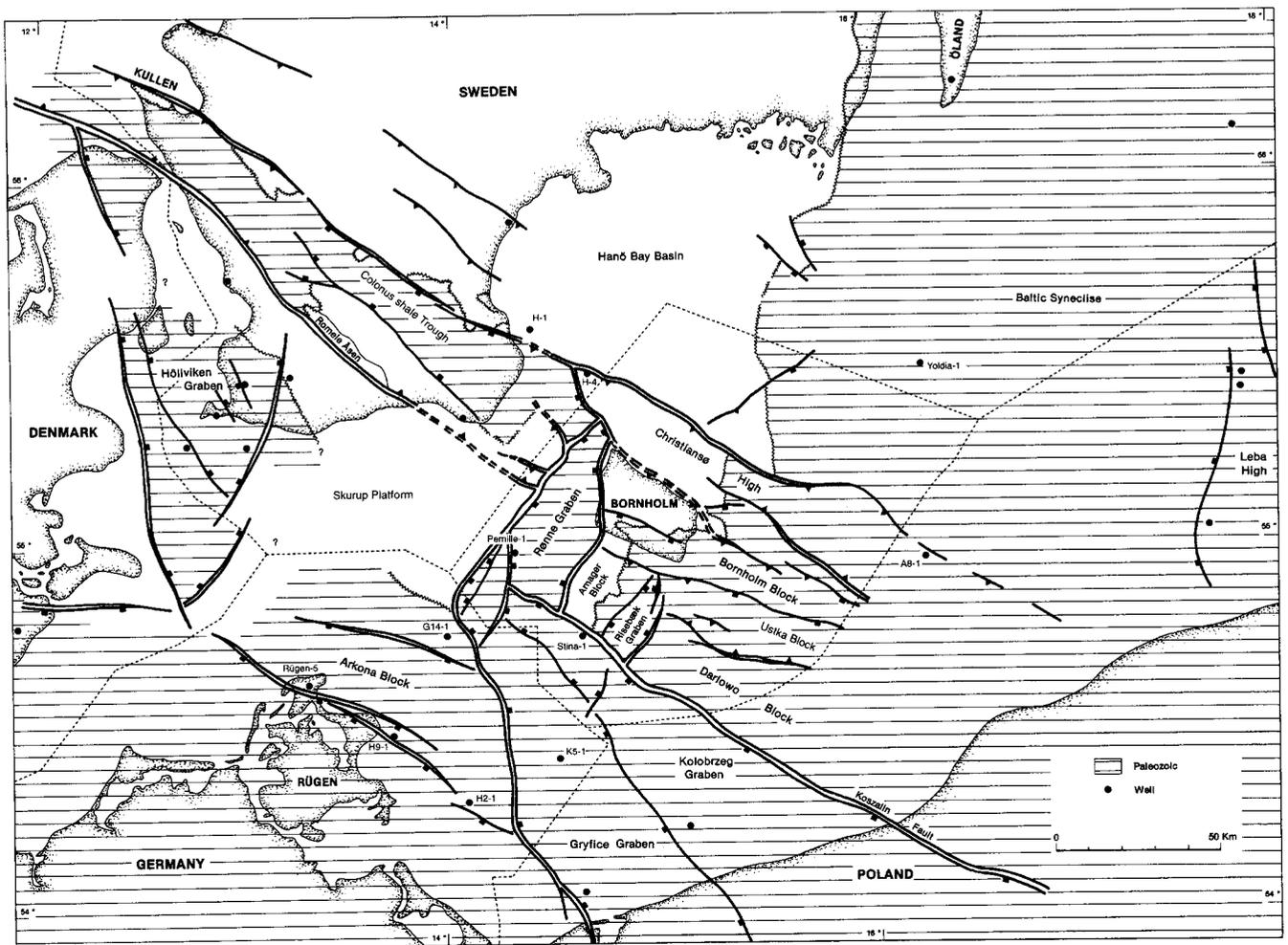


Fig. 1: Regional structural outline. The present distribution of Palaeozoic sediments is indicated (areas with ruling). Wells referred to in the text are also indicated.

# Structural outline

The study area straddles the Sorgenfrei-Tornquist Zone (sensu EUGENO-S working group 1988; hereafter referred to as STZ). In its southeastern continuation, this zone merges with the Teisseyre-Tornquist Zone in the Polish offshore. These zones form the boundary between the relatively stable Fennoscandian Shield/East European Platform to the northeast and the northwest European sedimentary basins to the southwest. The area southwest of the STZ is occupied by the Norwegian Danish Basin limited to the south along the Ringkøbing Fyn High. In contrast to the Teisseyre-Tornquist Zone which separates Precambrian basement from Phanerozoic basement, the STZ has Precambrian crystalline basement of similar radiometric age on either side (e.g. Pozaryski et al. 1979; EUGENO-S working group 1988). The Caledonian Deformation Front has been projected south of the Ringkøbing Fyn High (e.g. Piske and Neumann 1990; Vejrbæk 1990; Ziegler 1982). If present, the Caledonian Deformation Front is likely to have an approximately east - west orientation just north of Rügen and converge with the Koszalin Fault in Poland. The coincidence of the projected Caledonian Deformation Front with the Teisseyre-Tornquist Zone distinguishes the latter from the STZ (EUGENO-S working group 1988).

The study area consists of a complex system of horsts and grabens with a dominant NW-SE fault direction, paralleling the Sorgenfrei - Tornquist zone. These structural elements were formed in Late Palaeozoic or later times (Fig. 1). Recurrent tectonic movements have affected the area throughout the Phanerozoic.

The main structural elements are the Hanö Bay Basin (Kumpas 1980), the Baltic Syncline (e.g. Franke 1990), the Christiansø High (Andersen et al. 1975), the Skurup Platform (J. Bergström et al. 1982), the Rønne Graben, the Bornholm Block, the Arnager Block (earlier Southern Bornholm High; Vejrbæk 1985), the Risebæk Graben (earlier Arnager Graben; Vejrbæk 1985), the Darlowo Block, the Gryfice Graben, and the Kolobrzeg Graben (Dadlez 1974, 1976, 1977). These structural elements are described in more detail in the following paragraphs.

## *The Hanö Bay Basin and Baltic Syncline*

The Hanö Bay Basin and the Baltic Syncline are both part of the relatively stable East European Platform. They are both characterized by few, insignificant faults and gentle thickness variations. The Hanö Bay Basin is characterized by an up to 1km thick Upper Cretaceous succession of sandstones and limestones mainly resting directly on crystalline basement or separated by local thin veneers of older Mesozoic deposits. Well data from the Swedish off-

shore indicate these to be sandstones, claystones and coals of Rhaetian to Barremian age (Kumpas 1980). The sedimentary succession has its depocenter against the Christiansø High and is tapering off to the northeast. The basin stretches northwestwards to onshore Sweden (equivalent to the Christianstad Basin of J. Bergström et al. 1982), where it is thinning out. The Hanö Bay Basin forms a gradual transition to the Baltic Syncline along the westerly erosional limit of Palaeozoic sediments (see plate 2; Fig. 1). This erosional limit is proposed to define the eastern extension of the Hanö Bay Basin. Seismic data indicate that only thin and patchy occurrences of pre-Cretaceous sediments are present northwest of this line (Kumpas 1978). The Cambrian age assigned by Kumpas (1978) to these patches of presumed quartzite has, however, been questioned by J. Bergström (pers. comm.). Towards the east from this line, Palaeozoic sediments (dominated by shales) thicken, while the unconformably overlying Cretaceous sediments thin and eventually disappear. The Baltic Syncline is situated on the western margin of the East European Platform. It is bounded by the Baltic Shield to the north, by the Latvian Saddle to the east and by the Byelorussian Anteclise to the southeast. The southwestern margin is defined by the Teisseyre-Tornquist Zone (Brangulis et al. 1993).

## *The Christiansø High*

The Christiansø High is a NW-SE striking basement high mainly made up by a rotated basement block with a southwest dip. This geometry generates a narrow halfgraben-like structure with an elongated depocenter along the northeast coast of the island of Bornholm. The conformity of the infill sediments with the basement indicates the block rotation to be post depositional. Infill sediments are mainly of Late Cretaceous age. On the northeastern edge crystalline basement is exposed on the small islands of Ertholmene of which Christiansø is the most prominent.

The high probably came into existence during Late Cretaceous - Early Tertiary inversion. The faults defining the block show reverse net fault displacement consistent with the compressional tectonism of the inversion. In some places the faults show to have earlier had normal displacements before they were reversed. In some places the normal fault component has however, been completely obliterated by the subsequent inversion tectonism. The main fault defining the northeastern edge of the Christiansø High is more or less continuous with the fault defining the northeastern boundary of the Colonius Shale Trough in Sweden. This fault has normal fault segments in Sweden that are replaced by reverse segments along strike similar to the assumed nature of the Christiansø High fault (e.g. J.

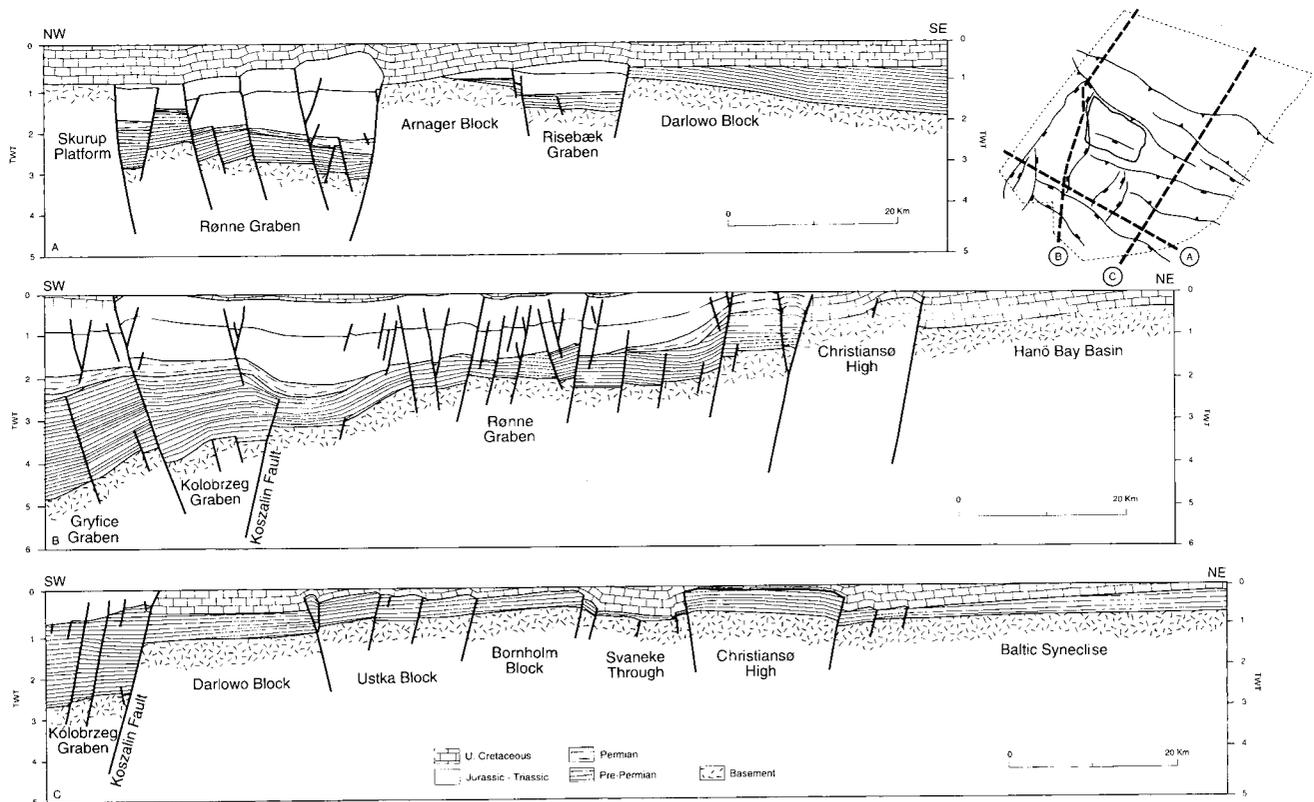


Fig. 2: Geosections around Bornholm with depths in TWT. Based on seismic interpretation.

Bergström et al. 1982). This fault is somewhat arbitrarily considered to constitute the northeastern limit of the Fenoscandian Border Zone.

Towards the southeast the structure of the Christiansø High becomes more complex before merging with the Hanö Bay Basin/Baltic Syncline. Additional reverse faults subdivide the block into the Christiansø High proper and the Svaneke Trough (Fig. 2), and significant thicknesses of Lower Palaeozoic occur. The fact that the Lower Palaeozoic succession has its greatest thickness on this portion of the Christiansø High, as compared to the adjacent blocks, suggests that the reverse faults defining the high were normal faults before compressional reactivation took place during the inversion phase.

### The Skurup Platform and Arnager Block

The Rønne Graben is limited by the Skurup Platform to the northwest and the Arnager Block and Bornholm proper to the southeast. Both blocks are characterized by up to 1.5 km Upper Cretaceous sediments, mainly resting directly on crystalline basement. The Skurup Platform is bounded to the northeast by the main fault defining the Romeleåsen. The Arnager Block adjoining the Rønne Graben has a sedimentary succession similar to that of the Skurup Platform. However, a wedge of Lower Palaeozoic and Jurassic/Triassic sediments is found next to the Risebæk Graben. This wedge thickens in the direction of the Risebæk Graben and slightly to the north.

### The Rønne and Risebæk Grabens

These two grabens are both NNE-SSW trending, the Røn-

ne Graben being the most prominent. The Rønne Graben was identified and named by Andersen et al. (1975) based on interpretation of gravity data. An earlier description of the Risebæk Graben was given by Vejrbæk (1985) under the name Arnager Graben. At present, the thickness of the Palaeozoic succession in the Rønne Graben is up to 1 sec. TWT, but generally around 0.7 sec. TWT corresponding to 1-1.5 km. The thickness is generally increasing towards the south in the transition to the Kolobrzeg and Gryfice Grabens (see below and plate 2). The transition between the Rønne and Kolobrzeg Grabens is constituted by the northwestern extension of the Koszalin Fault (fig. 1). This fault appears to die out before reaching the Skurup Platform. A local maximum thickness is found in the transition to the Colonus Shale Trough. A local minimum thickness, most likely caused by erosion, is found NE of the Koszalin Fault in the Rønne Graben next to the Arnager Block (earlier Southern Bornholm High; Vejrbæk 1985; see plate 2). Footwall uplift occurring contemporaneously with activity of the Koszalin Fault during the Carboniferous may have caused this local erosion (N. E. Hamann, pers. comm.).

Both Rotliegendes and Zechstein are present in the Rønne Graben (Fig. 7). The Rotliegendes, which is assumed to constitute the initial fill when the graben was formed, reaches 0.5 sec. TWT thickness corresponding to almost 1 km along the western margin of the graben, but is absent along parts of the east margin of the graben (Plate 1). This indicates rotation movements during graben subsidence, which continued through the later Mesozoic tectonic events as indicated by the Top Pre-Rotliegendes time structure map (Plate 4). The apparent slight anticlockwise rotation axis seen by a comparison between the Rotliegendes isopach map and the Top Pre-Rotliegendes time structure map (Plates 1 and 4) is partly attributed to a stronger inversion

uplift of the northern Rønne Graben as compared to the southern part during the Cretaceous to Early Tertiary inversion.

The Palaeozoic succession preserved in the Risebæk Graben is app. 0.5 sec. TWT corresponding to about 1 km, and only a few hundred msec. thicker than on either side; the main trend being a general westward thinning. This thinning may have been caused by foot-wall erosion along the eastern bounding fault of the Rønne Graben. Recurrent erosion of the Palaeozoic on the flanks of the Risebæk Graben is thus likely to have occurred during the Late Palaeozoic and most of the Mesozoic because of repeated downfaulting of the Rønne Graben. Downfaulting beginning in Triassic times of the Risebæk Graben has better preserved the Lower Palaeozoic succession. No seismic evidence for the presence of Rotliegendes in the Risebæk Graben is seen. It may be inferred that the area was eroded in Rotliegendes times and that initiation of the graben formation took place in the Triassic (see plate 1).

#### *The Bornholm, Ustka and Darlowo Blocks*

These are three parallel blocks with a NW-SE orientation with gentle southerly dip of sedimentary strata and accordingly a general decreasing basement depth in a northerly direction. The Ustka and Darlowo Blocks are extensions of structural elements defined in the Polish part of the Baltic sea (e.g. Dadlez 1974, 1976, 1977). The succession consists mainly of Lower Palaeozoic sediments, probably directly overlain unconformably by Upper Cretaceous strata. Even on the Darlowo Block, where maximum basement depths on these blocks of about 3 km are found, no seismic evidence seems to suggest the presence of sediments between the Cretaceous and Lower Palaeozoic packages. The Ustka and Bornholm Blocks are shallower equivalents, where the Bornholm Block constitute Bornholm proper and its southeastern extension. The blocks are separated by reverse faults that were active during the Late Cretaceous to Early Tertiary inversion phase, which mainly accounts for the present structural configuration. The faults may have been active as normal faults before the inversion, the activity being indicated by minor thickness changes of the Palaeozoic succession across the faults.

#### *The Gryfice and Kolobrzeg Grabens*

Both grabens are part of the Polish - Danish Trough (Dadlez 1974, 1976, 1977) and are bounded to the northeast by the Koszalin Fault, which may be defined as the northwest limit of the Sorgenfrei-Tornquist Zone. The depth to basement in these two grabens is estimated to exceed 5 km of which more than 2sec. TWT, corresponding to about 4 km infill, is made up by Palaeozoic strata. Greater thicknesses may be expected further southeast, beyond the Danish sector (Piske & Neumann 1990, 1993). The succession comprises Lower Palaeozoic as well as Carboniferous, Permian, Triassic, Jurassic and Cretaceous sediments. Most of the Palaeozoic north of the Caledonian Deformation Front is of Wenlockian and Ludlovian age. The Lower Palaeozoic was proven by the Stina-1 well to include at least Ludlovian (2118m-2210m) and Wenlockian (down to the total depth at

2518m). However, graptolite data from wells outside the study area suggest that rapid deposition commenced already in the Llandoveryan closest to the supposed Caledonian Deformation Front and successively later with increasing distance from this front (Bjerreskov, pers. comm.).

Upper Palaeozoic (Upper Carboniferous and Permian) sediments are proven by the German offshore well K5-1 (Rempel 1992) to extend from the Polish onshore north-westwards into these grabens. The Carboniferous exceeds 300 m in this well, and the Permian reaches 993.5 m of which 652 m is Rotliegendes. Seismic mapping shows that Rotliegendes (as well as Zechstein) extends further northwest and into the Rønne Graben. This is consistent with results from both the Pernille-1 well and the Stina-1 well (Fig. 7; plate 1). The interval 1813 m to 2118 m in the Stina-1 well is only tentatively referred to the Rotliegendes as no age-diagnostic fossils were obtained.

The present thickness of the Mesozoic succession locally exceeds 3 km. This may have been more in the past, since both (and especially the Kolobrzeg Graben) have suffered pronounced Late Cretaceous to Early Tertiary inversion tectonism, completely removing Upper Cretaceous sediments over large parts.

#### *The Caledonian Deformation Front*

There is no indication that the Caledonian Deformation Front coincides with any of the faults shown on the structural outline map (cf. Figs 1 and 4). However, well data and seismic data provide sufficient constraints to locate the boundary between unfolded and folded Lower Palaeozoic sediments within a narrow zone less than 20 km from the north tip of Rügen, obliquely across the Gryfice and Kolobrzeg Grabens before merging with the Koszalin Fault zone at the Polish coast (Piske & Neumann 1990). Internal reflections in the Lower Palaeozoic succession in seismic data from just north of Rügen show, and well data from Rügen suggest the presence of low angle thrusting (Piske & Neumann 1993; Katzung et al. 1993). The strike-slip emplacement of Caledonian terrains, which has been proposed by Brochwicz-Lewinski et al. (1981), Pozaryski et al. (1982) and Brochwicz-Lewinski (1984) may account for the narrow transition from deformed to undeformed Palaeozoic sediments, but this has been questioned by Dadlez (1983) and seems inconsistent with the observations at Rügen mentioned above. South of the 'Caledonian Deformation Front' sediments are intensely folded 'geosynclinal' greywackes and shales of Ordovician age with assumed primary thicknesses in excess of 3 km (Franke 1990). Jaeger (1967) regards these sediments to be no younger than Llandoveryan. In boreholes immediately south of the deformation front sediments are not reported to be metamorphosed, but are described to be folded, crushed and otherwise intensely deformed. In the North German offshore wells K5-1 and H2-1 Ordovician Shale were encountered with dips between 0° and 90°, abundant slickensides and fractures, - but still containing recognizable graptolites (Piske & Neumann 1993). Further south metamorphosis has led to the formation of phyllites (Dadlez 1977).



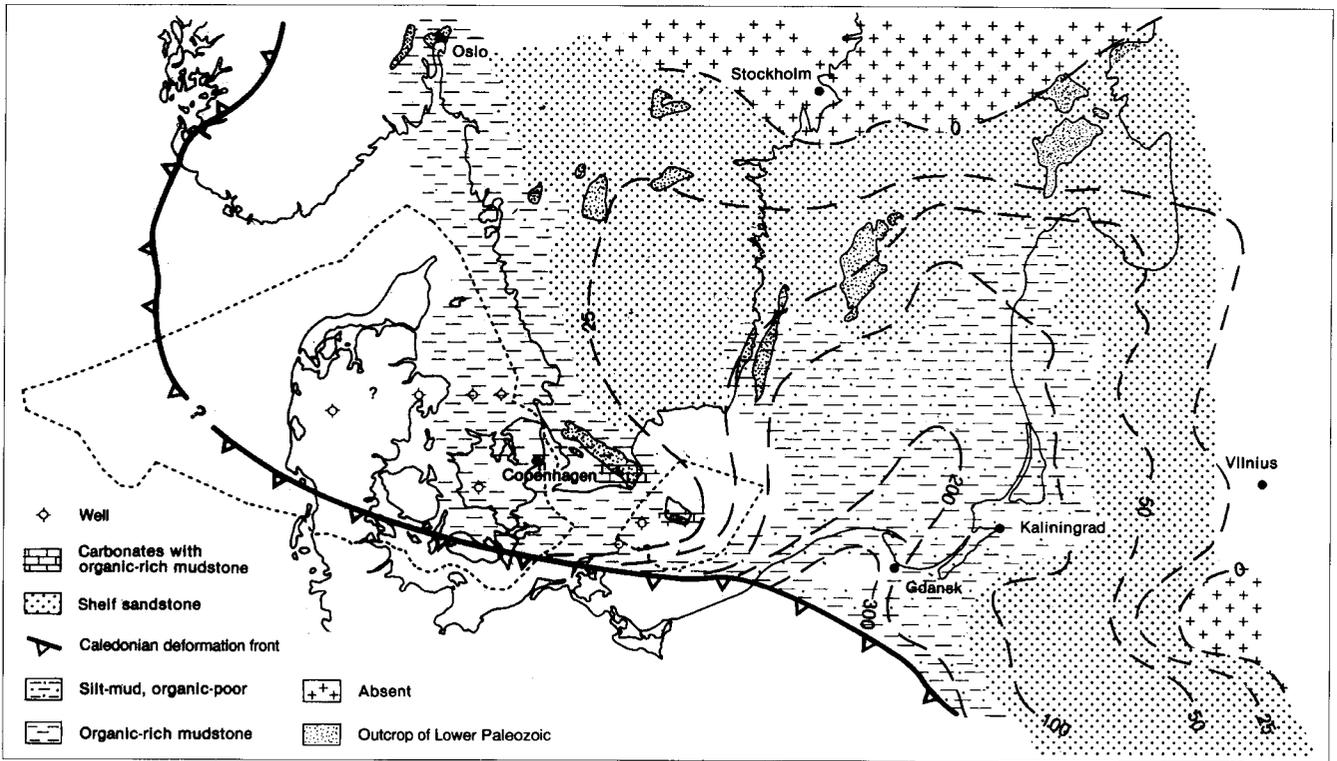


Fig. 4: Distribution and generalized isopachs of the Middle Cambrian sandstone and correlative facies. In Polen: Tyna Sandstone and Veselovsk Formation, in Lithuania and Kaliningrad: Deimena and Veselovsk Formations, in Latvia: Deimena Formation, in Estonia: Ruhnu Beds, and in Sweden: Lingulid Sandstone (Hagenfeldt 1989).

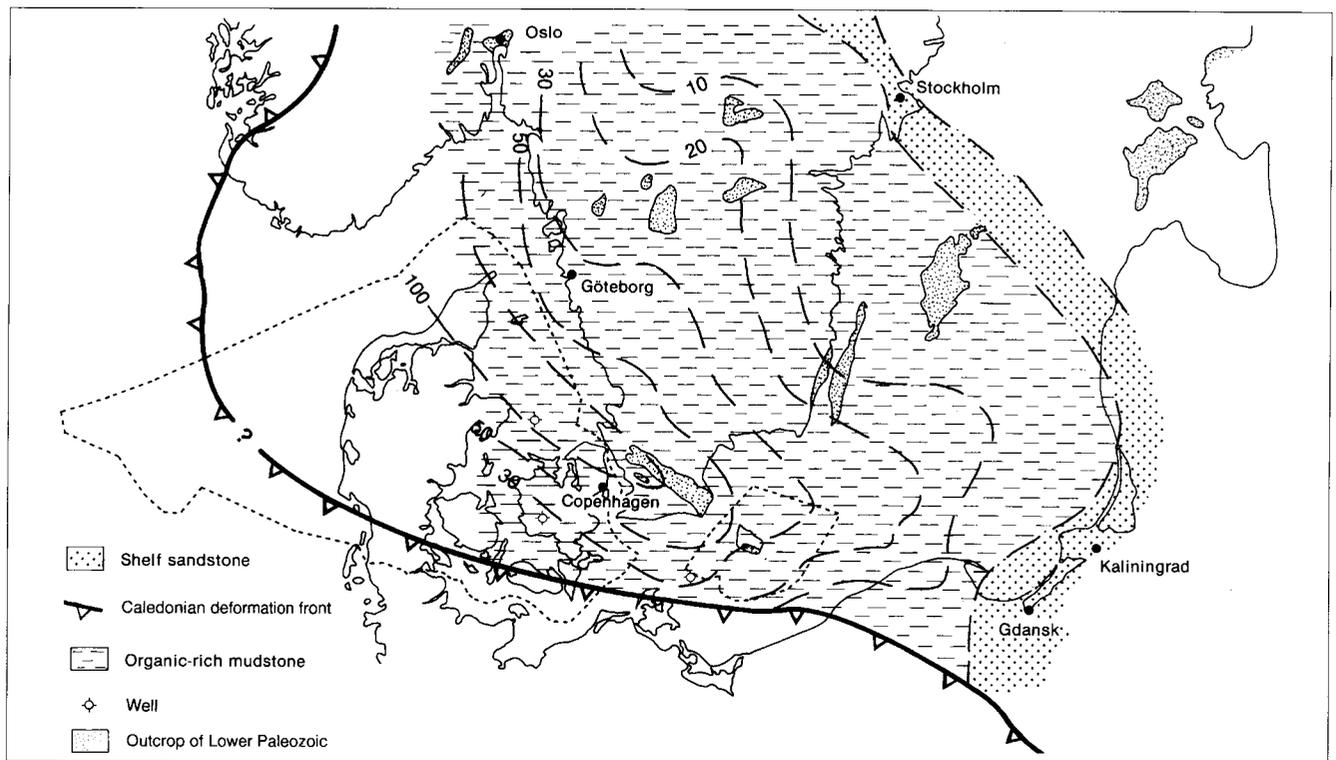


Fig. 5: Original distribution and generalized isopachs of main source rock, the Upper Cambrian Upper Alum Shale and Dictyonema Shale (see Fig. 3). Note the elongated depocenter, which to some extent coincides with the Colonius Shale Trough in Scania.

setting and is widely distributed (Gee 1972; J. Bergström & Gee 1985). The Alum Shale is enriched in Ba, Va, Mo and U (Armands 1972; Andersson et al. 1985). Time equivalent sandy deposits consisting of glauconitic, fine sands and minor shales and were deposited in open oxic littoral-

shallow shelf environment. The two depositional facies; one fine clastic and one organic rich mudstone, are separated by a relatively narrow transitional belt (Fig. 4).

The Middle Cambrian to earliest Ordovician cycle ended with a major regression, depositing glauconitic sands in shallow water areas and a thin but laterally extensive limestone unit (*Ceratopyge* Shale and *Ceratopyge* Limestone). Isopach patterns for the Middle Cambrian sandy sediments of the Alum Shale Group (Fig. 5) exhibit a distribution pattern generally similar to that of the outline of the Baltic Syncline but the existence of an additional NW-SE trough in Scania is indicated coinciding with the present day Colonius Shale Trough (Fig. 5). The period ended with uplift of the Bornholm block including the area around the German well G-14 (Franke 1990). The uplifted region possibly extended into northern Poland (the "erhobene Tafelrand" of Modlinski 1975, 1977). The uplifted ridge may have extended as far to the northwest as to include Scania and parts of the Kattegat (exemplified with the Terne-1 well; Michelsen & Nielsen 1991), if we judge from the general stratigraphic variation.

#### *Early to Middle Ordovician (493 - 450 Ma)*

The Early Ordovician (Arenigian) to Middle Ordovician (Caradocian) began with a prominent change in the sedimentary facies on the shelf from predominantly fine clastic marine sediments to carbonate marine sediments. The carbonates comprise marls and limestones, at times glauconitic and grading into calcareous claystones. The organic rich clay facies persisted in areas next to the shallow shelf facing deeper waters. Intermediate facies comprise glauconitic, calcareous sands. From the beginning of the Early Ordovician volcanic ashes (K-bentonite or meta-bentonite) reached the region and the input of ashbeds culminated in the Caradocian (S. Bergström & Nilsson 1974; Huff et al. 1992). One of the ashbeds, the so-called "Big Bentonite Bed" (454 Ma), has been traced over large distances providing a precise timeline for the Balto-Scandic region (S. Bergström & Nilsson 1974; Huff et al. 1992). The series of ashbeds can be recognized in the succession encountered in the Terne-1 well in the Kattegat area (Michelsen & Nielsen 1991). The ash was derived from eruptions in a continental crust-based, destructive plate-margin within the Iapetus region of the Caledonides (Huff et al. 1992).

The Bornholm region remained uplifted until the deposition of the Komstad Limestone (Arenigian). After the deposition of the carbonates in the Bornholm Region sediment accumulation apparently stopped (Fig. 3). This could be interpreted as the area remained subaerially exposed until the eruption of the "Big Bentonite Bed" which is situated at the base of the *Dicellograptus* Shale (Gry 1948; S. Bergström & Nilsson 1974). Contemporaneous uplifts with depressions and ridges are recorded in the Leba area in northern Poland (Fig. 1; Modlinski 1977).

To the southwest of Bornholm and in a NW-SE trending belt from Rügen-western Pomerania (northwestern Poland) about 800-1100 m of graptolitic shales and greywackes-silty-arenaceous intercalations were formed (Fig. 3; Jaeger 1967; Franke 1967, 1990; Dadlez 1977).

#### *Middle to Late Ordovician (450-439 Ma)*

Following the volcanic ashfall a change in the sedimentary and faunal regime occurred on the shelf (Jaanusson 1976; Männil 1990), whereas the shale deposition of the outer shelf areas in Scania, Bornholm and northern Poland remained in graptoliferous shale facies (J. Bergström et al. 1982; Bjerreskov & Stouge 1985; Podhalanska 1980). Extensive carbonate mound building began on the inner shelf in the middle Caradocian (Kullsberg Limestone and equivalents in the subsurface of Gotland, Baltic sea and Baltic countries). The mound building culminated with formation of the Boda Limestone in the Late Ordovician. The stromatolite mounds function as unsealed reservoirs with minor oil shows in the Siljan area in Sweden (Auton 1980) (Fig. 8). In the subsurface south of Gotland the mounds are targets for oil exploration. Near the mounds, debris deposits (coquinoid limestones) are present showing that the mounds formed topographic highs on the seabottom. Distally, marls and shales predominate. This mound building was promoted by the foundering of the outer shelf, possibly due to loading of the craton margin. The loading was caused by thrustsheets emplaced during the Taconic phase of Caledonian Orogeny.

During the Ashgillian, the Elblag depression in northern Poland received its maximum amount of sediments (Modlinski 1977, 1982). The interval ended with the lithological change from black graptolite shales to grey mudstones of the Jerrestad and Tommarp Formations in the Scania, Bornholm and the Leba areas. A prominent hiatus is developed at the Ordovician - Silurian boundary on the inner shelf (Männil 1990), and on top of the prominent carbonate mounds of the Boda Limestone (Jaanusson 1982). The Upper Ordovician-Lower Silurian hiatus was caused by a eustatic low due to glaciations during this time (Spjeldnæs 1981; Brenchley et al. 1994). Sediments from the *D. clingani* Zone and the Jerrestadian Stage are missing in NW Scania (J. Bergström et al. 1982) and a similar hiatus is found in the Kattegat in the Terne-1 well. The hiatus was caused by a combination of uplift of this area in the Late Ordovician and the above mentioned glacioeustatic event (Fig. 3).

#### *Early to Late Silurian (439- 425 Ma)*

Deposition of the Lower Silurian started with the relatively rapid latest Ordovician - Llandoveryan transgression and formation of the *Rastrites* Shale, which covered the whole platform. The dual facies distribution with carbonates on the inner shelf and shales on the outer shelf persisted from the Late Ordovician. The early Llandoveryan constitutes a lull in tectonic activity, but with continuing clastic input to the region. Graptolite data indicate that fast sedimentation began in the Llandoveryan in areas closest to the Caledonian Deformation Front (Bjerreskov, pers. comm.). Dark shales and increasing volcano-clastic influxes in the *Cyrtograptus* Shale (Bjerreskov & Jørgensen 1983), however, were formed in the late Llandoveryan on the outer shelf.

Volcanic activity, resulting in the deposition of volcanic ashes and tuffaceous beds, continued in the Wenlockian

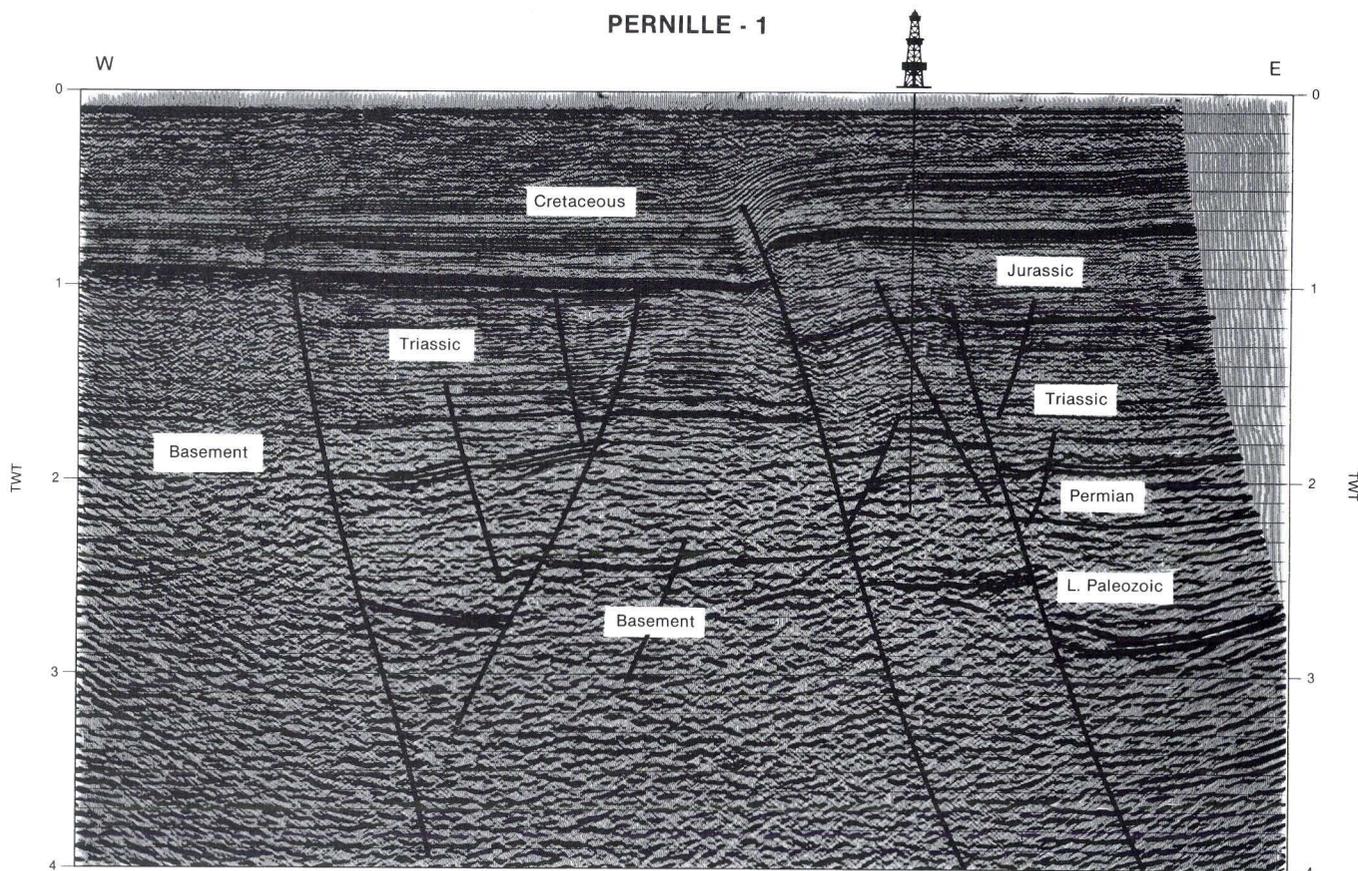


Fig. 6: Seismic section (NH87B-101) through the Pernille-1 well.

(Jeppsson & Laufeld 1986; Bjerreskov & Jørgensen 1983; Bjerreskov 1986). The sources of the volcano-clastics were probably located to the south and southwest of the region and may relate to the thrusting of the Caledonides towards the northwest as part of the early phases of the Scandian orogeny (Bassett 1985; Berthelsen 1992).

Carbonate deposition on Gotland and in the eastern Baltic regions includes shallow water variable facies with mounds facing towards the southeast and with deeper water marl sedimentation in front of the mounds. The transition from the shallow water carbonates to deeper water deposits is gradual, suggesting a ramp-like configuration of deposition (Frykman 1989). The central Scania and Kattegat regions were subsiding and continuous sedimentation associated with increasing deepening prevailed. Depositional patterns were increasingly influenced by the Caledonian orogenic zone to the SW of Bornholm, Scania and north-west Poland. During the Wenlockian the subsidence accelerated and the depocenter moved towards the northeast and hemipelagic and turbiditic sedimentation prevailed south of Bornholm (Pernille-1; Figs 6, 7). At this time the carbonate mound facies on the inner shelf broke down to a mosaic of shallow water facies (Riding 1981).

#### Late Ludlovian to late Early Devonian (425-390 Ma)

The youngest Caledonian deposits of the north German-Polish Caledonian cycle are Late Silurian to Early Devonian in age. Closure of the Danish-German-Polish Caledonian foldbelt took place during Wenlockian-Ludlovian. The depocenter for the rapid clastic sedimentation in front of

the foldbelt continued to move north-northeast in Late Silurian times.

The transition from the Late Wenlockian to Ludlovian is marked by a lithological change and by regional regression. The Ludlovian *Colonus* Shale is about 600 m thick in Scania where the sediments were deposited, preserved in the *Colonus* Shale Trough. Lindström (1960) and Laufeld et al. (1975) suggest that this trough, which extends in a NW-SE direction through Scania, was formed at the time of deposition of the *Colonus* Shale. Approximately 300 m of sediments was deposited at the location of the Terne-1 well in the Kattegat. In the A-8 well in the Polish offshore (east of Bornholm) more than 1500m sediments were deposited (Grigelis 1991).

After the peak of the Caledonian Orogeny the regressive marine carbonate of the shelf moved towards the south and later the Old Red Sandstone continental sedimentation took over (Riding 1981; Bassett 1985). In the Scania and Kattegat the marine calcareous shale, mudstones, siltstones and limestone (Bjärsjölagård Limestone) and on top red continental deposits are referred to the Öved-Ramsåsa Group (Jeppsson & Laufeld 1986). The fauna suggests that the Öved-Ramsåsa Group is latest Silurian (Ludlovian-Pridolian) (Martinsson 1967). In Poland on the East European Platform marine deposits are of Pridolian age and are overlain by Red Devonian Sandstones (Tomczykowa 1988). Sediments of the Öved-Ramsåsa Group are not proven to be present in the Bornholm area, but are likely to be present in the offshore. However, in the Rønne Graben offshore Bornholm Wenlockian beds are known to be unconformably overlain by Rotliegendes sediments as seen in the Pernille-1 well (Figs 6, 7).

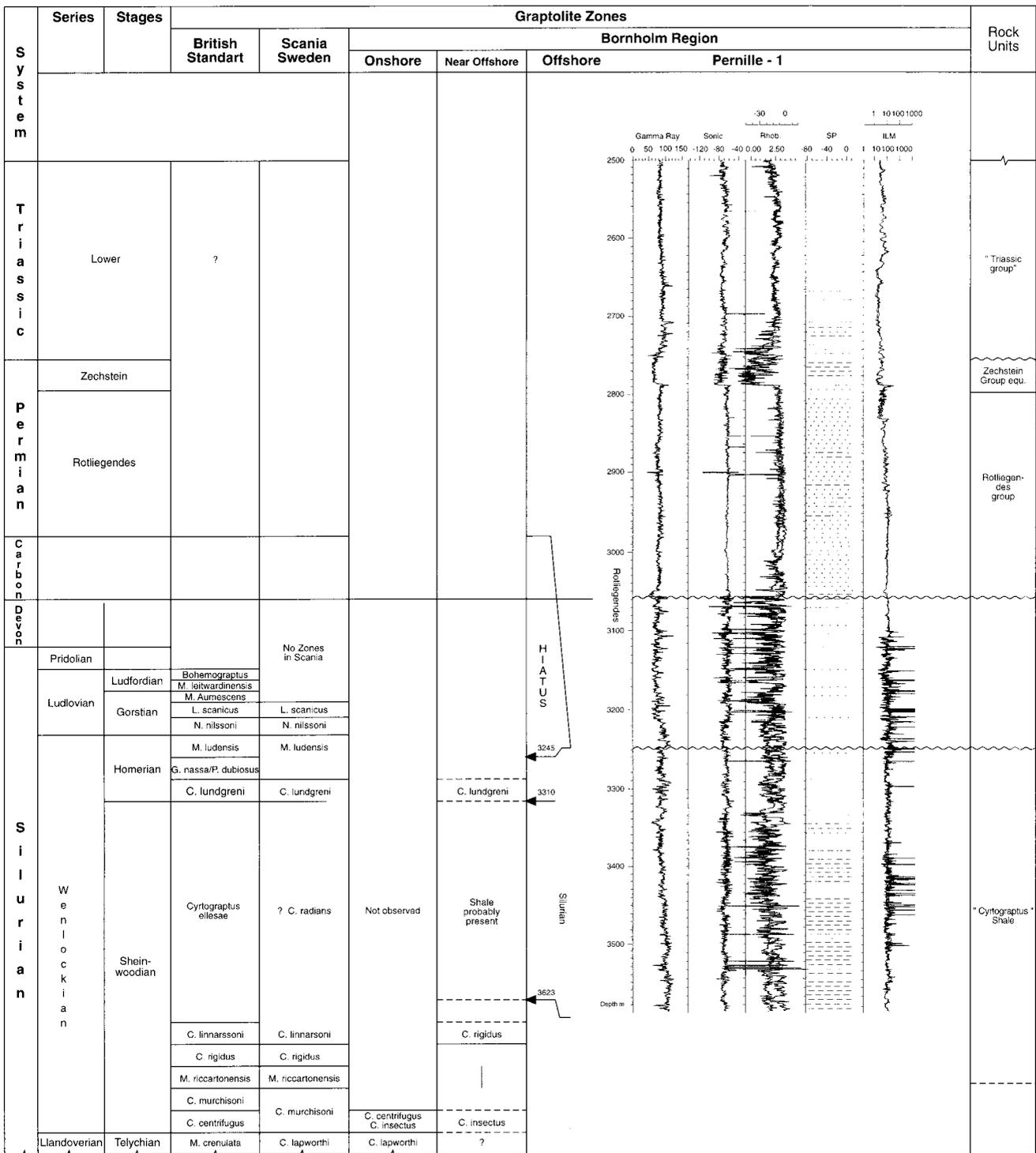


Fig. 7: Palaeozoic stratigraphy of the Pernille-1 well.

### Late Palaeozoic

The Scania-Bornholm-northern Poland region is marked by denudation during Devonian time. Middle Devonian is resting unconformably on deformed Lower Palaeozoic strata south of the Caledonian Deformation Front (Piske & Neumann 1993) thus indicating an early Devonian erosion phase. Reworked Carboniferous spores and pollen have been recorded from the Jurassic succession in Scania (Guy-Ohlson et al. 1987) and on Bornholm (Nielsen & Koppelhus 1991) indicating that Carboniferous sediments once covered the Bornholm and/or adjacent areas and later have been removed before the deposition of the Lower Permian sediments. Today significant thicknesses of pre-

served Middle Devonian to Lower Carboniferous are preserved only south of the Caledonian Deformation Front (Piske & Neumann 1993) and in the eastern Baltic (Grigelis 1991). An unconformity between Lower and Upper Carboniferous strata encountered in wellbores south of the Caledonian Deformation Front document a second significant phase of erosion to have occurred in the Middle Carboniferous (Piske & Neumann 1993).

Rotliegendes includes sediments consisting of varicoloured fluvialite clastic sediments dominated by sand. Rotliegen-

des overlie the Lower Palaeozoic offshore sequence unconformably (Pernille-1; Figs 6, 7). One age-diagnostic palynomorph pointing to an Early Carboniferous age was obtained from the Rotliegendes interval, but is interpreted to be reworked. Otherwise no fossil evidence supports the interpretation of the interval as being Rotliegendes. The Rotliegendes sediments mark the initial filling of the Rønne Graben, which was initiated as a rotational fault block as showed by the wedge shape of the Rotliegendes graben fill (cf. plate 1). Approximately 250 m corresponding to almost 200 msec TWT of Rotliegendes is encountered in

the Pernille-1 well (Fig. 7), but thicknesses of up to 500 msec TWT corresponding to over 600 m have been mapped seismically (cf. plate 1).

Thin shaly equivalents to Zechstein Group sediments are also present in the Pernille-1 well (Fig. 7). The Zechstein is a calcareous claystone with abundant palynomorphs that gives the age.

# Discussion on the subsidence history and hydrocarbon maturation

The following chapter deals mainly with the hydrocarbon aspects of the Palaeozoic in the Bornholm area. Consequently, a brief account of the likely reservoirs and source rocks is given. Main emphasis is however placed on critical factors of the likely maturation history based on burial modelling. The necessary assumptions for burial modelling with respect to reconstruction of missing section are summarized through the construction of a set of palinspastic profiles.

## *Possible reservoirs*

Some hundred metres of laterally extensive Cambrian fluvial - shallow marine sand- and siltstones belonging to the Nexø Sandstone, the Hardeberga Sandstone, the Norretorp Formation and the Rispebjerg Sandstone are present on the island of Bornholm. Reservoir quality is, however, poor and is expected to deteriorate with increased depth of burial.

Middle Cambrian sandstones known from onshore and offshore of Sweden (*Lingulid* Sandstone; Hagenfeldt 1989), Latvia and Lithuania (Deimena Sandstone; Brangulis et al. 1992) are not present on the island of Bornholm. These sandstones are known reservoirs for oilfields in Latvia, Lithuania and the Kaliningrad region of Russia. Similar sandstones are not found onshore Bornholm, which agrees with the observed westward increase in shale proportion (Brangulis et al. 1992; Zabels et al. 1992). It is, however, considered possible that similar Middle Cambrian sands may be present in the northeastern portions of the Bornholm offshore area as is suggested by the presence of Middle Cambrian sand beds in the A8-1 well in the Polish offshore (Grigelis 1991: 100). In the eastern Baltic the porosities of these sandstones range from 1-2% to 25 - 28%, with permeabilities in the range 0.1 - 1500 mD (Brangulis et al. 1992).

Ordovician reefal oil reservoirs are known from the island of Gotland and from Dalarna (Auton 1980). Occurrences of reefal type reservoir rocks in the Bornholm offshore are possible, but they are expected to be of limited size, similar to onshore Gotland. Oolitic limestones associated reefal structures are found to possess porosities up to 20% with a mean of 10-12% in the eastern Baltic (Brangulis et al. 1992). However, the small size renders them questionable as exploration targets in an offshore setting.

Upper Silurian continental sandstones are known from southern Sweden (Öved-Ramsåsa Sandstone; Ludlovian-Pridolian), and thick beds of similar sand are expected to be present in the Bornholm offshore. They are expected to

be of poor reservoir quality due to poor sorting and great depth of burial.

The most promising of these potential reservoirs is the Middle Cambrian sandstone, as it is the main reservoir of the largest oilfields in the Baltic region (Brangulis et al. 1992), followed by the Ordovician reefal carbonates. Neither of these have yet been proven in the Bornholm area. A likely location to search for them in the Bornholm area is considered to be in the western Baltic Syncline adjacent to the eastern Hanö Bay Basin.

## *Possible source rocks*

In the Baltic Syncline mature petroleum source rocks are present in the Swedish offshore, in Lithuania and adjacent territories in Russia and in Poland. The Cambro-Ordovician Alum Shale in Sweden contains as much as 17.5% TOC and is locally oil-prone with oil-yields upon pyrolysis on the order of 4-8% (Andersson et al. 1985). The Alum Shale has been mined in several places as oil shale (e.g. Närke, Öland). The maturity generally decreases from overmature with respect to oil in the Bornholm area, in a northeasterly direction. The northernmost occurrence of mature Alum Shale in the vicinity of the Bornholm area is on the south tip of Öland (S. Bergström 1980; Fig.8).

Investigations of immature to mature Alum Shales from Sweden show that they represent excellent oil source rocks (Andersson et al. 1985). Biomarkers obtained from the oil found on Gotland indicate the Alum Shale as the likely source rock (Dahl et al. 1989). The lack of mature source rock on Gotland and the fact that the closest known mature Alum Shale is found on the south tip of Öland (S. Bergström 1980) suggests migration distances of more than 100 km. The Alum Shale is also the main source rock to the oilfields in Baltic republics, where Cambrian Alum Shales has TOC values of 3-17 % and Ordovician Alum Shales has TOC values of about 13 % (Brangulis et al. 1992).

At present the Alum Shale is post-mature or a gas source rock on Bornholm. Similar organic matter is expected in Ordovician and Silurian shales, but the concentration of organic matter is significantly lower, although this to some extent is compensated for by greater thicknesses.

Carboniferous coal-bearing deposits are well-known sources for gas in Germany and Poland. Oil fields, probably sourced from bituminous intervals in the Zechstein, are known in Poland and eastern Germany. Carboniferous source rocks are only considered interesting in the southernmost part of the Bornholm area. Westphalian has been

proven in the German K5-1 well, just outside the Danish sector, probably confined to the Gryfice Graben (Piske and Neumann 1993). The maturity is late to post mature with TOC values reaching 1% (Rempel 1992).

### Palinspastic profiles

Important assumptions in the point-wise maturity modelling described below may be synthesized with the palinspastic reconstructions shown in Fig. 9. The idealized profile extends from a position south of the postulated Caledonian Deformation Front to an arbitrary point in the Baltic sea south of Öland. Main assumptions/interpretations are summarized in the following. The initial profile illustrates that the region could be described as a stable platform with slow sedimentation and minor thickness variations (Fig. 8). To the south "geosynclinal" sedimentation (mainly Ordovician) is inferred to account for the thick deformed Ordovician found on Rügen. The thick deposits that later were deformed during Caledonian Orogeny may also range into the Silurian (Dadlez 1974).

In the late Early to Late Silurian, Caledonian collision tectonics are inferred to have taken place to the south causing folding and uplift of the "geosynclinal" sediments (Fig. 8). This resulted in tectonic loading of the southern platform edge and ample supply of erosion products to fill the thereby created "foreland" basin. This mechanism accounts for the regional rapid shaledominated deposition associated with little faulting and for the primary thickness increase towards the Caledonian Deformation Front. Some faults are assumed to have been active contemporaneously to account for some of the present thickness variation in the Palaeozoic. Maturity modelling shows the main maturation

of the Lower Palaeozoic to have taken place from this time to the Permian. The presence of these faults is important to account for more abrupt changes in regional maturity variations, and in forming possible barriers to early migration. Possible candidates for these faults could be the north-eastern fault bounding the Christiansø High and the Koszalin Fault (cf. profile C, Fig. 2), which could account for the suggested change from a post mature state onshore Bornholm to a mature state in the Baltic Syncline east of the Hanö Bay Basin.

A Devonian erosional phase is documented in northern Poland (Dadlez 1977; Tomczykowa 1988). It is assumed to be rather uniform over the investigated area for simplicity since no data indicate otherwise. Before the transition to the Mesozoic graben tectonism, regional deposition of Devonian and Lower Carboniferous is inferred. Presence of most of the Devonian is documented in the eastern Baltic (Grigelis 1991: 173) and in wells offshore Rügen (the H9-1 well; Rempel 1992). The former presence of Carboniferous in the Bornholm area is suggested by the presence of reworked Carboniferous spores in Jurassic sediments (Guy-Ohlson et al. 1987; Nielsen & Koppelhus 1991) and by the extra burial required to fit maturity profiles. A palynomorph obtained from the Rotliegende in the Pernille-1 well was age-diagnostic for the Early Carboniferous, thus suggesting that these former sediments at least in part could be Lower Carboniferous.

A pronounced late Carboniferous - early Permian uplift is proposed to occur in conjunction with volcanic activity and the initiation of the Sorgenfrei-Tornquist Zone. Differential block movements are assumed to have started at this time,

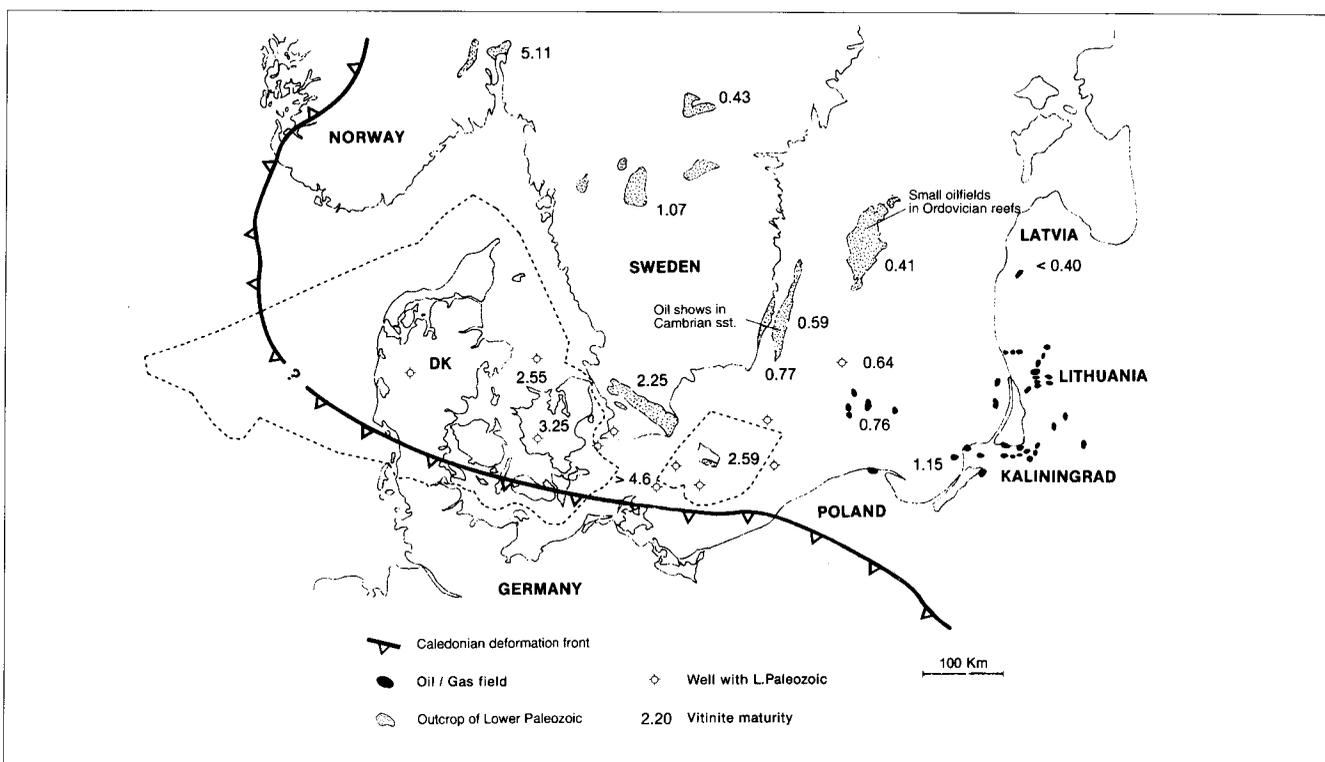


Fig. 8: Regional map of vitrinite maturity observations in the Cambrian Alum Shale. Location of oil/gas fields that are assumed to be sourced from the Alum Shale is also shown. Note the increase in maturity from Öland to Bornholm.

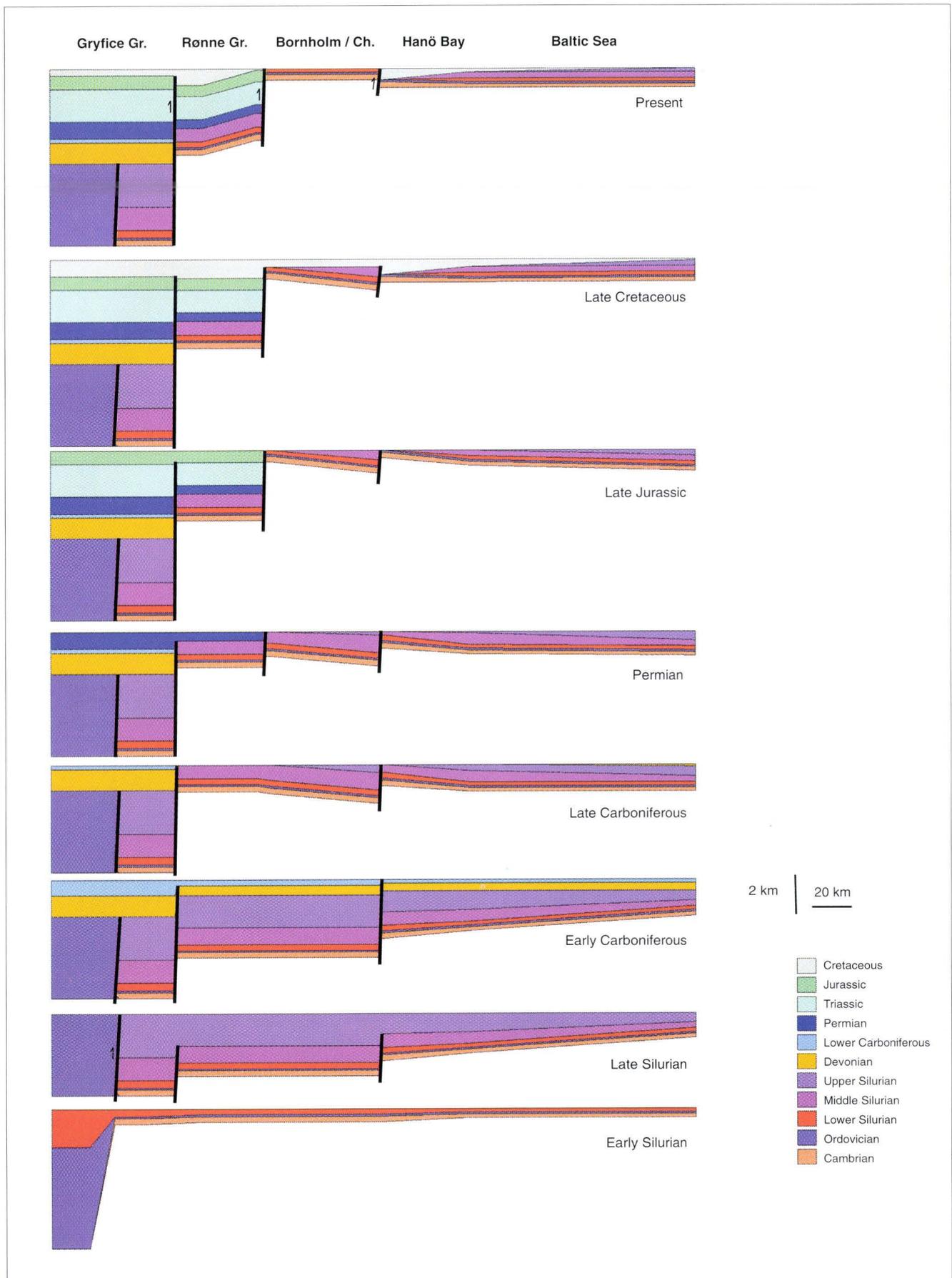


Fig. 9: Schematic palinspastic reconstruction of a profile from the Gryfice Graben (near Rügen) across the Bornholm area into the Baltic (near southern tip of Öland). Neither decompaction nor lateral palaeo-water variations have been included in the reconstruction.

corresponding to the initiation of the Mesozoic graben systems. Consequently, the amount of erosion varies dependant on the position in relation to the structural features that were active during the Mesozoic. As indicated on the palinspastic profile, erosion is assumed to be deepest close to the growing depocentres, which also includes the location of the not yet initiated Rønne Graben. In contrast, the most actively subsiding parts, exemplified by the Gryfice Graben, were eroded the least. The area around the Pernille-1 well in the Rønne Graben was in a foot-wall position initially relative to the Kolobrzeg/Gryfice Grabens, as indicated by the deep erosion of the Palaeozoic. This erosion is evidenced by pronounced maturity differences across the basal unconformity of the Mesozoic in the Pernille-1 well. The amount of uplift characterizing the flanks of the actively subsiding areas (i.e. the Sorgenfrei-Tornquist zone) diminishes proportionally with distance. Consequently the erosion in the Baltic syncline east of the Hanö Bay Basin is less than in the Pernille-1 well area. The amount of preserved Palaeozoic is also a consequence of primary accumulated thickness. Preserved thickness is therefore not greater than in the Rønne Graben in spite of less erosion east of the Hanö Bay Basin. In the Hanö Bay Basin proper, the amount of erosion cannot be assessed, because all Lower Palaeozoic has been removed. The Rønne Graben is assumed to have been initiated in the Permian, as recorded by the Rotliegenden sediments in the Pernille-1 well, subsequent to the erosion phase (see also Plate 1).

Rift tectonics continued through the Mesozoic. Grabens subsided contemporaneously with continued uplift of foot-wall areas, including the Bornholm island. Triassic and Jurassic subsidence of the Rønne Graben and the Gryfice Graben is similar as documented by the sedimentary record. The subsidence was punctuated by late Jurassic - early Cretaceous phases of minor erosion and non-deposition in both grabens. Concurrently the Hanö Bay Basin was being uplifted ("footwall" uplift) to act as source for the graben fill sediments.

During Late Cretaceous, the rift tectonics gradually ceased and gave way to regional subsidence and was eventually replaced by inversion tectonism. The inversion caused former normal faults to be reversed, some places with reverse components in excess of 1 km (profile A, Fig. 2). Pronounced inversion is documented to have occurred already in the Campanian (Erlström 1994). The largest amounts of uplift are found in the former graben areas. Reverse faulting was in places sufficiently severe to turn former small grabens into horst structures as is evident for instance for the eastern portion of the Christiansø High (profile C, Fig. 2).

### *Maturity modelling*

The reconstruction of the Palaeozoic subsidence history has been constrained by modelling of the maturation history (Fig. 10). A number of wells or pseudo-wells have been modelled of which three sets of tentative burial graphs with maturity developments are shown in Fig. 10. The burial graphs and maturity modelling are based on the Yüklér model (Yüklér et al. 1978). The thicknesses and assumed

	<b>Gryfice Graben</b>	<b>Pernille-1 well</b>	<b>Hanö Bay Basin</b>
Cenozoic	500	-128	-200
Upper Cretaceous	850	966	800
Lower Cretaceous	200	-291	100
Jurassic	900	900	200
Triassic	1700	1197	-200
Permian	900	468	200
Upper Carboniferous	-600	-2700	-2000
Lower Carboniferous	800	300	200
Devonian	1100	500	400
Ludlovian	2300	1700	1100
Wenlockian	1200	900	700
Lower Silurian	400	300	300
Ordovician	100	100	100
	300	300	300

*Table 2: Amount of deposited (not decompacted) and eroded thicknesses (as negative numbers) during different time intervals. These correspond to what has been used in the subsidence modelling and palinspastic reconstruction.*

erosion magnitudes are listed in Table 2 in a simplified form.

Thicknesses (and magnitudes of erosion) are not decompacted, to allow direct comparison with drilled sections.

The inferred primary thicknesses of eroded successions have been constrained by regional considerations and by constraints imposed by maturity indicators. Each point is not sufficiently constrained by maturity indicators and other relevant data to allow a reliable isolated evaluation of the subsidence history, especially considering erosion phases. However, when several points are modelled in combination so that they comply with the same general geological development and geological evidence from all neighbouring points, each point may be modelled with higher confidence. Main assumptions with respect to lateral geological consistency are described in the previous section.

The maturity indicators show that the Lower Palaeozoic in the Rønne Graben and the southern areas is post mature. This also applies to the Lower Palaeozoic found onshore Bornholm, where maturities are high (Buchardt & Lewan 1990). Oxygen and carbon isotope data from the onshore exposed Lower Palaeozoic have been interpreted to show that its high maturity was attained through deep burial (Buchardt & Nielsen 1985).

The Palaeozoic development is consistent in the three diagrams by assuming a regional thickness increase towards the former plate boundary (towards the Caledonian Deformation Front) as discussed for the palinspastic profiles. This is reflected as different amounts of subsidence. This thickness increase is to some extent documented by seismic data, but is assumed to have been much more uniform than seen today. The reason for this assumption is the observed angular unconformable relationship of the Lower Palaeozoic to overlying strata, and the high maturity of the

organic matter in exposed Palaeozoic sediments (Buchardt & Nielsen 1985; Goodarzi et al. 1988).

An important similarity between the burial diagrams is the consistent indication of the main phase of maturation in Silurian - Late Palaeozoic time. The present maturity distribution is thus suggested to be controlled mainly by the basin geometry prior to the Permian. For hydrocarbon exploration, it is therefore important to establish a likely model for the Late Palaeozoic basin geometry. The only

place considered possible for finding Alum Shale still in the oil window at the present time, within the Bornholm area, is in the Hanö Bay Basin as shown on the burial diagram. The likelihood for this is dependant on how fast the primary thickness of the Lower Palaeozoic decreases towards the north-northeast. A step in the primary thickness is inferred along the northeastern bounding fault of the Christiansø High as is discussed above, which accounts for the favourable modelled maturity as of today.

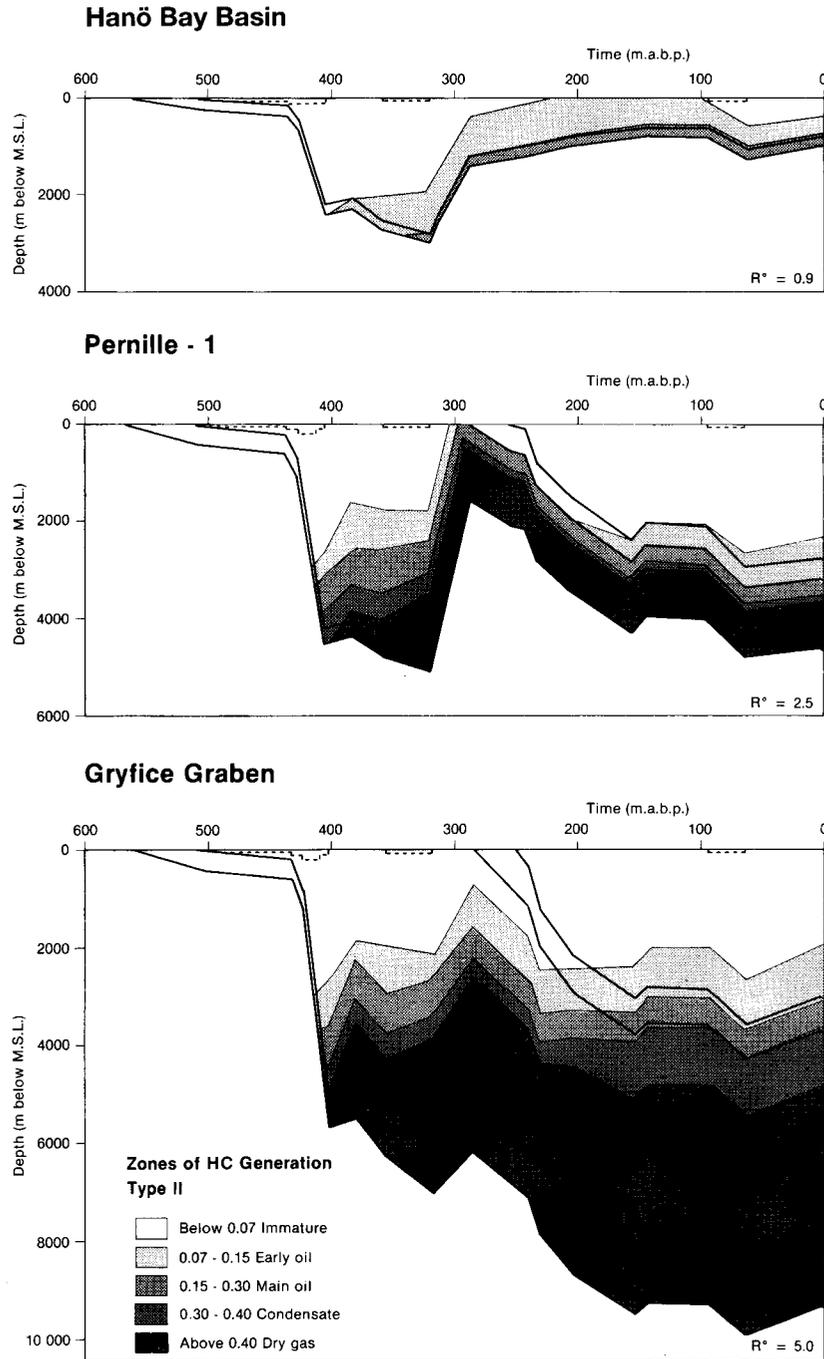


Fig. 10: Calculated burial and maturation development at 3 selected locations. The calculation is done with the Yüklér modelling software (Yüklér et al. 1978).

# Conclusion

Knowledge of the Bornholm area (especially the offshore area) has greatly improved with the acquisition of high quality seismic data and deep well data. Presence of Rotliegendes sediments in the Bornholm offshore has for instance been proved with the Pernille-1 well.

The present structural configuration of the Palaeozoic strata is a result of a complex tectonic history. However, the hydrocarbon potential with respect to the Palaeozoic evolution of the area may still be rather simple. Basin modelling, supported by observations, show that the present maturity is to a large extent a consequence of late Early to Late Palaeozoic burial. Maturity data and the present structural relationship of the Palaeozoic also suggest that a broad foreland type basin with a simple thickness increase in the direction towards the Caledonian Deformation Front may have existed before it was obscured by the tectonism and erosion occurring from Late Palaeozoic times to the present. The primary control on maturity patterns by former Palaeozoic burial opens the possibility that the Alum Shale in the northeastern portion of the Bornholm area may still be within the oil window. The new well data from the Bornholm area constrain the rapid burial responsible for the high maturity to have occurred already in Wenlockian times. In contrast, data from Scania and the Polish offshore suggest that the time of rapid deposition did not start before Ludlovian, thus indicating a slightly decreasing age of rapid deposition with distance from the Caledonian Front.

The post Precambrian geological development of the study area may be divided into three main evolutionary phases:

**A pre-rift development encompassing the Lower Palaeozoic sediments with an assumed generally relatively uniform thickness increase in the direction of the supposed Caledonian Deformation Front located to the south. The Palaeozoic development may be further subdivided into three sub-phases:**

*A period of slow sedimentation on a stable platform comprising the Cambrian through Early Silurian. The sedimentary succession commences with sandy sediments, but is dominated by shales and also has subordinate carbonates.*

*A period of foreland type sedimentation with rapid sedimentation commencing in the latest Llandoveryan to Wenlockian, continuing into the Ludlovian and possibly reaching into the Devonian. The change in tectonic regime may have been heralded already in the Caradocian. This period is characterized by folding and uplift of the Caledonides to the south causing tectonic loading of the foreland and rapid sedimentation of the erosional products arriving from the south. The sediments are predominantly shales.*

*Possible phase of gravitational collapse during which widespread Carboniferous sedimentation is thought to have taken place. The character of these sediments is unknown since they have been largely removed by erosion.*

**A syn-rift phase characterized by sedimentation in grabens and expanding basins. The sediments comprise Rotliegendes red beds, Permian marls and clays, Triassic (mainly continental) variegated sandstones, siltstones, shales and minor carbonates, and Jurassic to Lower Cretaceous (paralic to marine) clay, sand, marl, coal and subordinate carbonates. This phase is likely to have been initiated and controlled by a Late Carboniferous- Early Permian tensional dominated right-lateral wrench fault system within the Sorgenfrei-Tornquist zone (J. Bergström et al. 1987, 1990).**

**Post-rift development phase dominated by Late Cretaceous limestone and sandstone sedimentation. During Late Cretaceous and Early Tertiary times the area was strongly affected by inversion tectonism caused by compressional strike-slip movements. This resulted in reverse faulting and uplift and erosion of former basinal areas. Deformation was probably multiphase (Liboriussen et al. 1987; Erlström 1994).**

Understanding the syn- and postrift phases is important for understanding the present structural configuration and distribution of the Lower Palaeozoic succession.

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## References

- Andersen, O. B., Larsen, B. & Platou, S. W. 1975: Gravity and Geological structures of the Fennoscandian Border Zone in the Southern Baltic. *Bulletin of the Geological Society of Denmark* 24(1), 45-55.
- Andersson, A., Dahlman, B., Gee, D. G., & Snäll, S. 1985: The Scandinavian Alum Shales. *Sveriges geologiska Undersökning, Serie. Ca* 56, 50 pp.
- Armands, G. 1972: Geochemical studies of uranium, molybdenum and vanadium in a Swedish Alum Shale. *Stockholm Contributions in Geology* 27, 1-148.
- Auton, C. 1980: The presence of oil within the Ordovician limestone mounds of the Siljan district, central Sweden. *Bulletin of the Geological Institutions of the University of Uppsala, New Series* 9, 1-4.
- Bassett, M. G. 1985: Silurian stratigraphy and facies development in Scandinavia. In Gee, D. G. and Sturt, B. A. (eds.) *The Caledonide Orogen - Scandinavia and related areas, Pt. 1*, 283-292. John Wiley and Sons Ltd.
- Bergström, J. & Ahlberg, P. 1981: Uppermost Lower Cambrian biostratigraphy in Scania, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 103(2), 193-214.
- Bergström, J., Holland, B., Larsson, K., Norling, E. & Sivhed, U. 1982: Guide to excursions in Scania. *Sveriges geologiska Undersökning, Serie Ca* 54. 95 p.
- Bergström, J. & Gee, D. G. 1985: The Cambrian in Scandinavia. In Gee, D. G. and Sturt, B. A. (eds.) *The Caledonide Orogen - Scandinavia and related areas, Pt. 1*, 247-271. John Wiley and Sons Ltd.
- Bergström, J., Kumpas, M. G., Pegrum, R. M. & Vejgåk, O. V. 1987: Kimmerian and Alpine evolution of the northwestern part of the Tornquist zone. *Zeitschrift für Angewandte Geologie* 33(8), 198-200.
- Bergström, J., Kumpas, M. G., Pegrum, R. M. & Vejgåk, O. V. 1990: Evolution of the northwestern part of the Tornquist zone - part 1. *Zeitschrift für Angewandte Geologie* 36 (2), 41-45.
- Bergström, S. M. 1980: Conodonts as palaeotemperature tools in Ordovician rocks of the Caledonides and adjacent areas in Scandinavia and the British Isles. *Geologiska Föreningens i Stockholm Förhandlingar* 102, 377-392.
- Bergström, S. M. & Nilsson, R., 1974: Age and Correlation of the Middle Ordovician Bentonites on Bornholm. *Bulletin of the Geological Society of Denmark* 23, 27-48.
- Berthelsen, A. 1992: Mobile Europe. In Blundell, M. D. Freeman, R. & Mueller, S. (eds.) *European Geotraverse*, 11-32. Cambridge University Press.
- Bjerreskov, M. 1986: Silurian graptolites from deep well Maglarp 1, Scania, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 108(1), 1-12.
- Bjerreskov, M. & Jørgensen, K. A. 1983: Late Wenlock graptolite-bearing tuffaceous sandstone from Bornholm, Denmark. *Bulletin of the Geological Society of Denmark* 31, 129-149.
- Bjerreskov, M. & Stouge, S. 1985: Field excursions guide, Bornholm, Denmark. 3rd International Conference, Graptolite working group of the International Palaeontological Association. 23 pp. Copenhagen.
- Brangulis, A. P., Kanev, S. V., Margulis, A. S. & Haselton, T. M. 1992: Hydrocarbon Geology of the Baltic Republics and the adjacent Baltic Sea. In Spencer, A. M. (ed.): *Generation, Accumulation and Production of Europe's Hydrocarbons II*, Special Publication of the European Association of Petroleum Geoscientists No. 2. 111-115. Springer-Verlag, Berlin Heidelberg.
- Brangulis, A. P., Kanev, S. V., Margulis, L. S. & Pomerantseva, R. A. 1993: Geology and hydrocarbon prospects of the Palaeozoic in the Baltic Region. In Parker, J. R. (ed.) *Petroleum Geology of Northwest Europe. Proceedings of the 4th. Conference*, 651-656. The Geological Society, London.
- Brenchley, P. J., Marshall, J. D., Carden, G. A. F., Robertson, D. B. R., Long, D. G. F., Meidla, T., Hints, L. & Anderson, T. F. 1994: Bathymetric and isotopic evidence for a short-lived Late Ordovician glaciation in a greenhouse period. *Geology* 22, 295-298.
- Brochwicz-Lewinski, W. 1984: Sinistral Strike-slip movements in central Europe in the Palaeozoic. *Publication of the Institute of Geophysics, Polish Academy of Sciences. Warsaw, A-13*, 160, 3-13.

- Brochwicz-Lewinski, W., Pozaryski, W. & Tomczyk, H. 1981: Mouvements coulissants de grande ampleur au Paléozoïque inférieur le long de la marge sud-ouest de la plate-forme Est-Européenne. (Large scale Early Palaeozoic strike-slip faulting along the margin of the East European platform). *Comptes Rendus des Séances de L. Académie de Sciences, Série 2* (11), Vol. 293 855-858, Paris.
- Buchardt, B., & Lewan, M. D. 1990: Reflectance of vitrinite like macerals as a thermal maturity index for Cambro-Ordovician Alum Shale, southern Scandinavia. *American Association of Petroleum Geologists, Bulletin* 74(4), 394-406.
- Buchardt, B., & Nielsen, A. T. 1985: Carbon and oxygen isotope composition of Cambro-Silurian limestone and antraconite from Bornholm: evidence for deep burial diagenesis. *Bulletin of the Geological Society of Denmark* 33, 415-435.
- Dadlez, R. 1974: Some geological problems of the Southern Baltic Basin. *Acta Geologica Polonica* 24(1), 261-275.
- Dadlez, R. 1976: Zarys Geologii Podloza Kenozoiku w Basenie Poludniowego Baltyku. Z badan geologicznych morza, Tom. I. Instytut Geologiczny Biuletyn 285, 22 p.
- Dadlez, R. 1977: Tectonic position of western Pomerania (Northwestern Poland) prior to the Upper Permian. *Instytut Geologiczny Biuletyn* 274, 49 - 82.
- Dadlez, R. 1983: O koncepcji Wczesnopaleozoicznych wielkich ruchow przesuwczych wzdłuż krawędzi płyty Laurentyjskiej i Baltyckiej. (On the concept of a major Early Palaeozoic wrench movement along the edges of Laurentian and Baltic Plates.). *Przegląd Geologiczny, XXXI* no. 6, 377-386.
- Dahl, J., Chen, R. T. and Kaplan, I. R. 1989: Alum Shale bitumen maturation and migration: implications for Gotland's oil. *Journal of Petroleum Geology* 12(4), 465-476.
- Erlström, M. 1994: Evolution of Cretaceous sedimentation in Scania. *Lund Publications in Geology* 122, 36 pp.
- EUGENO-S Working Group 1988: Crustal structure and tectonic evolution of the transition between the Baltic Shield and the North German Caledonides (the EUGENO-S Project). *Tectonophysics* 150, 253-348.
- Franke, D. 1967: Der erste Aufschluss im tieferen Palaeozoicum Norddeutschlands und seine Bedeutung für die Tectonische Gliederung Mitteleuropas. *Jahrbuch für Geologie, Bd. 1*, 119-165, Berlin.
- Franke, D. 1990: The north-west part of the Tornquist-Teisseyre Zone - platform margin or intraplate structure? *Zeitschrift für Angewandte Geologie* 36, (2), 45-48.
- Frykman, P. 1989: Carbonate ramp facies of the Klinteberg Formation Wenlock-Ludlow transition on Gotland, Sweden *Sveriges geologiska Undersökning, Serie C* 820, 79 pp.
- Gee, D. G. 1972: The regional geological context of the Tåsjö uranium project, Caledonian Front, central Sweden. *Sveriges geologiska Undersökning, Serie C* 671, 36 pp.
- Gee, D. G. 1987: The Scandinavian Alum Shales - Mid Cambrian to Tremadoc deposition in response to early Caledonian subduction. *Norsk geologisk Tidsskrift* 67, 233-235.
- Goodarzi, F., Stasiuk, L. D. & Lindholm, K. 1988: Graptolite reflectance and thermal maturity of Lower and Middle Ordovician shales from Scania, Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 110(3), 225-236.
- Grigelis, A. A. (ed.) 1991: *Geology and Geomorphology of the Baltic Sea (in Russian)*. Lithuanian Geological Institute. 419 pp. Leningrad: Nedra.
- Gry, H. 1948: Bentoniten i Bornholms Ordoviciem. *Meddelelser fra dansk geologisk Forening* 11, 364-385.
- Guy-Ohlson, D., Lindquist, B. & Norling, E. 1987: Reworked Carboniferous spores in Swedish Mesozoic sediments. *Geologiska Föreningens i Stockholm Förhandlingar* 109(4), 295-306.
- Hagenfeldt, S. 1989: Middle Cambrian acritarchs from the Baltic Depression and south-central Sweden, taxonomy and biostratigraphy. *Stockholm Contributions in Geology* 41, 177-250.
- Hamberg, L. 1991: Tidal and seasonal cycles in a Lower Cambrian shallow marine sandstone (Hardeberga Fm.) Scania, Southern Sweden. In Smith, D.G., Reinson, G. E., Zaitlin, B.A. and Rahmani, R.A. (eds.) *Tidal Sedimentology*. Canadian Petroleum Geology Memoir 16, 255-274.
- Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. and Smith, D. G. 1989: *A geological timescale*. 263 pp. Cambridge University press, Cambridge.
- Holm, P. M. 1985: Bornholmske bjergarters temperaturer gennem tiden, K, Ar i mineraler. *Varv* (4), 117-125.
- Huff, W. D., Bergström, S. M. & Kolata, D. R. 1992: Gigantic Ordovician volcanic ash fall in North America and Europe: Biological, tectonomagmatic, and event-stratigraphic significance. *Geology* 20, 875-878.
- Jaanusson, V. 1976: Faunal dynamics in the Middle Ordovician (Viruan) of Balto-Scandia. In Bassett, M.G. (ed.) *The Ordovician System: Proceedings of a Palaeontological Association symposium*, Birmingham, September 1974, University of Wales Press and National Museum of Wales, Cardiff, 301-326.
- Jaanusson, V. 1982: The Siljan district. In D. L. Bruton and S. H. Williams (eds.): *Field excursion guide. IV International symposium on the Ordovician system*. Oslo-Norway. *Palaeontological Contributions from the University of Oslo*, 279, 15-43.
- Jaeger, H. 1967: Ordoviz auf Rügen Datierung und Vergleich mit anderen Gebieten. (Vorläufige Mitteilung). *Ber. deutsch. Ges. geol. Wiss., A, Geol. Paläont.*, 12 (1/2), 165-176. *Bereichte der deutschen Gesellschaft für geologische Wissenschaften, Geologie und Paläontologie*.
- Jaeger, H. 1984: Einige aspekte der geologischen entwicklung Sudskandinaviens im Altpaläozoikum. *Zeitschrift für Angewandte Geologie* 30, (1), 17-33.
- Jeppsson, L. & Laufeld, S. 1986: The Late Silurian Öved-Ramsåsa Group in Skåne, South Sweden. *Sveriges geologiska Undersökning, Serie Ca* 58, 45 pp.
- Katzung, G., Giese, U., Walter, R. & Von Winterfeld, C. 1993: The Rügen Caledonides, northeast Germany. *Geological Magazine* 130(5), 725-730, Cambridge University Press.
- Kumpas, M. G. 1978: Distribution of sedimentary rocks in the Hanö Bay and south of Öland. *Stockholm Contributions in Geology* 31 (3), 95-103.
- Kumpas, M. G. 1980: Seismic Stratigraphy and Tectonics in the Hanö Bay. *Stockholm Contributions in Geology* 34 (4), 35-168.
- Kunk, M., Bergström, S. M. & Sutter, J. 1986: A comparison of Middle Ordovician bentonites in Sweden and North America using Ar/Ar age spectrum dating techniques. *Terra Cognita* 6, p. 141.
- Laufeld, S., Bergström, J. & Warren, P. T. 1975: The boundary between the Silurian Cyrtograptus and Colonus Shales in Skåne, southern Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 97, 207-222.
- Liboriussen, J., Ashton, P. & Tygesen, T. 1987: The tectonic evolution of the Fennoscandian Border Zone in Denmark. *Tectonophysics* 137, 21-29.
- Lindström, M. 1960: On sedimentary and tectonic structures in the Ludlovian Colonus Shale of Scania. *Geologiska Föreningens i Stockholm Förhandlingar* 82, 319-341.
- Männil, R., 1990: The Ordovician of Estonia. In Kaljo, D. & Nestor, H. (eds.) *Field Meeting Estonia 1990. An Excursion Guidebook*. Institute of Geology, Estonian Academy of Science., Subcommittee on Ordovician Stratigraphy, IUGS Subcommittee on Silurian Stratigraphy, IUGS Project "Global Bioevents" IGCP, 11-20.
- Martinsson, A. 1967: The succession and correlation of ostracode faunas in the Silurian of Gotland. *Geologiska Föreningens i Stockholm Förhandlingar* 89, 350-389.
- Martinsson, A. 1974: The Cambrian of Norden. In Holland, C.H. (ed.) *Lower Palaeozoic Rocks of the World. Vol. 2: Cambrian of the British Isles, Norden and Spitsbergen*, 185-283. J. Wiley and Sons.
- Michelsen, O. & Nielsen, L. H. 1991: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark. Hans-1, Sæby-1, and Terne-1 wells. *Danmarks geologiske Undersøgelse, Serie A*, 29, 37 pp.
- Modlinski, Z. 1975: Podstawowe zmiany facjalne i miazoscioowe ordowiku platformowego polnocno-wschodniej Polski. *Kwartalnik Geologiczny* 19(3), 503-514.
- Modlinski, Z. 1977: Über die Ausbildung des Ordoviziums am Südwestrand der Osteuropäischen Tafel in der Polen. *Zeitschrift für Angewandte Geologie* 23 (9).
- Modlinski, Z. 1982: Rozwoj litofacjalny i paleotektoniczny ordowiku na obszarze platformy prekambryjskiej W polsce. (In Polish with english Abstract). *Prace Instytutu Geologicznego CII*, 66 pp.
- Nielsen, L.H. & Koppelhus, E. 1991: Reworked Carboniferous palynomorphs from the Lower Jurassic of Bornholm and their palaeogeographic significance. *Bulletin of the Geological Society of Denmark* 38, 253-266.
- Odin, G. S. and Odin, L. 1990: Echelle Numérique des temps géologiques. *Géochronique* 35, 12-21.
- Palmer, A.R. & James, N.P. 1980: The Hawke Bay Event: a circum-lapetus regression near the Lower-Middle Cambrian Boundary. In Wones, D.R. (ed.) *The Caledonides in the U.S.A. (Proceedings, IGCP project 27: Caledonide Orogen, 1979 meeting, Blacksburg, Virginia)* Department of Geological Sciences, Virginia Polytechnic Institute and State University, Memoir 2, 15-18.
- Piske, J. & Neumann, E. 1990: Zur Ausbildung der Ablagerungen des Altpaläozoikums im Gebiet der südwestlichen Ostsee. *Zeitschrift für Angewandte Geologie* 36, (9), 342-346.
- Piske, J. & Neumann, E. 1993: Tektonische Gliederung des prävariszischen Untergrundes in der südwestlichen Ostsee. *Geologisches Jahrbuch, Hannover*, A131, 361-388.
- Podhalanska, T. 1980: Stratigraphy and facial development of Middle and Upper Ordovician deposits in the Leba Elevation (NW Poland). *Acta geologica polonica* 30, (4), 327-390.

- Pozaryski, W., Brochwicz-Lewinski, W. & Jaskowiak-Schoeneichowa, M. 1979: The Geology of the Southern Baltic: Some Remarks. Bulletin de L'Académie Polonaise des Sciences 26 (2), 119-125.
- Pozaryski, W., Brochwicz-Lewinski, W. & Tomczyk, H. 1982: Sur le caractère hétérochronique de la Ligne Teisseyre-Tornquist, entre Europe centrale et orientale (On the Heterochroneity of the Teisseyre-Tornquist Line between Central and Eastern Europe). Comptes Rendus des Séances de L'Académie de Sciences, Série 2 (6), Vol. 295 691-696, Paris.
- Regnell, G. 1960: The Lower Palaeozoic of Scania. In: Regnell, G. and Hede, J. E.: The Lower Palaeozoic of Scania. The Silurian of Gotland. Guide to excursions. International Geological Congress, XXI session Norden 1960, guide to excursions nos A22 and C17, 3-43.
- Rempel, H. 1992: Erdölgeologische Bewertung der Arbeiten der Gemeinsamen Organisation Petrobaltic in deutschen Schelfbereich. Geologisches Jahrbuch, Reihe D, H 99, Hannover, 32 p.
- Riding, R. 1981: Composition, structure and environmental setting of Silurian bioherms and biostromes in northern Europe Society of Economic Paleontologists and Mineralogists, Special Publication 30, 41-83.
- Spjeldnæs, N. 1981: Lower Palaeozoic palaeoclimatology. In Holland, C. H. (ed.) Lower Palaeozoic rocks of the world, Vol. 3. Lower Palaeozoic of the Middle East, eastern and southern Africa, and Antarctica, 199-256. John Wiley and Sons, Chichester.
- Tomczykowa, E. 1988: Silurian and Lower Devonian Biostratigraphy and Palaeoecology in Poland. Instytut Geologiczny 359, Geology of Poland, VIII, 21-41.
- Vejbæk, O. V. 1984: Tectonic development of sedimentary basins offshore Bornholm. Geologiska Föreningens i Stockholm Förhandlingar 106(4), 396-397.
- Vejbæk, O. V. 1985: Seismic Stratigraphy and Tectonics of sedimentary basins around Bornholm, Southern Baltic. Danmarks geologiske Undersøgelse, Serie A, 8, 30 p.
- Vejbæk, O. V. 1990: The Horn Graben and its relationship to the Oslo Graben and the Danish Basin. In Neumann, E.-R. (ed.), Rift zones in the continental crust of Europe - Geophysical, Geological and Geochemical Evidence: Oslo - Horn Graben. Tectonophysics 178, 29-49.
- Yükler, M. A., Cornford, C. & Welte, D. 1978: One-dimensional model to simulate geologic, hydrodynamic and thermodynamic development of a sedimentary basin, Geologischen Rundschau 67 (3), 960-979.
- Zabels, A. J., Fridriksone, A. I., & Brangulis, A. P. 1992: Comparison of profiles for the Cambrian and Vendian in the eastern portion of the Baltic sea (in russian), in Palaeontology and stratigraphy for the Phanerozoic of Latvia and the Baltic Sea. Latvian university, geological department, Riga, pp. 110-119.
- Ziegler, P. A. 1982: Geological Atlas of Western and Central Europe. Elsevier, Amsterdam, 130 pp. and encl.

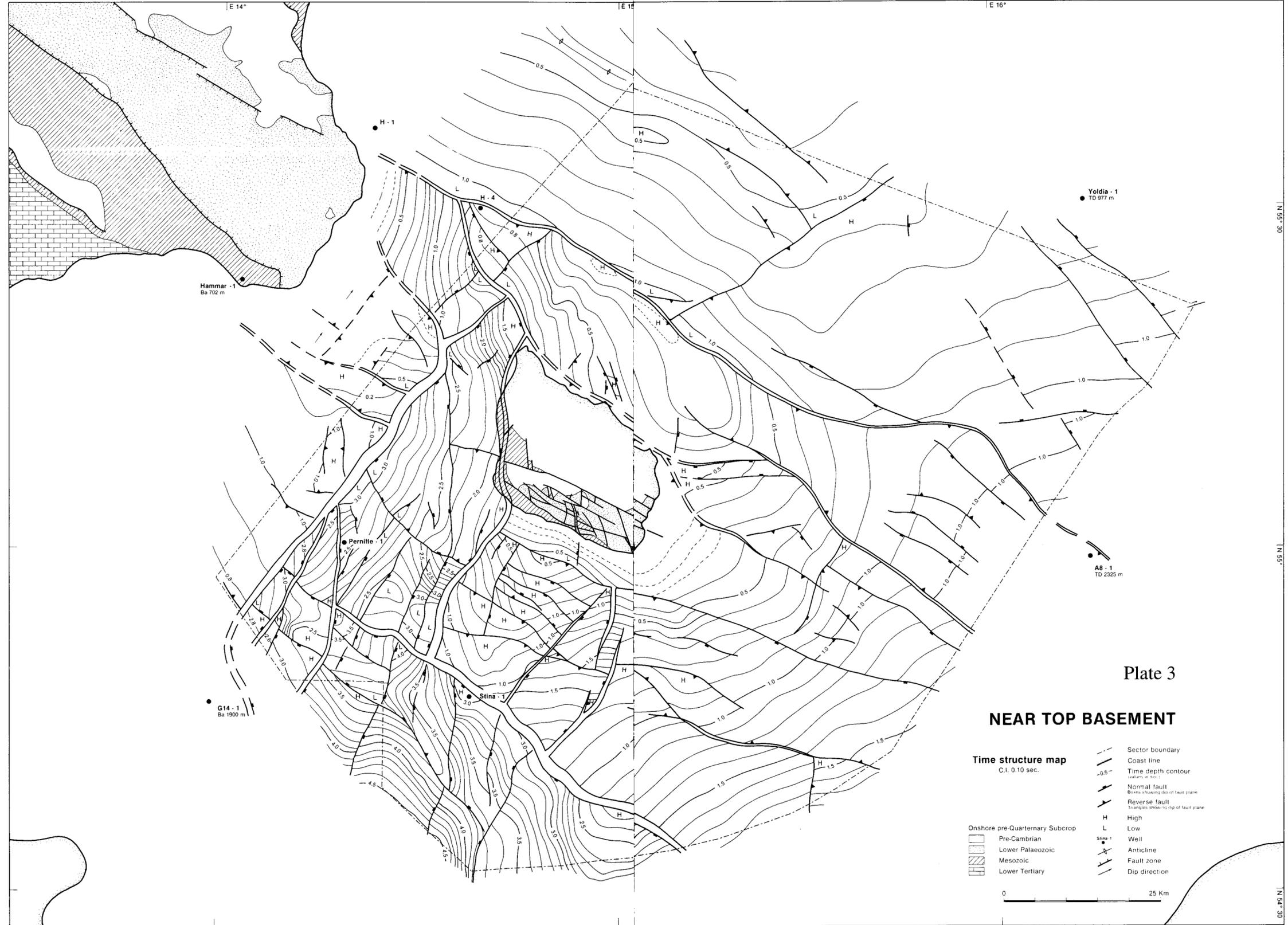


Plate 4

NEAR TOP PRE - ROTLIEGENDE



G14 - 1  
Pal. at 1200 m



**Plate 3**  
**NEAR TOP BASEMENT**

- Time structure map**  
C.I. 0.10 sec.
- Onshore pre-Quaternary Subcrop
    - Pre-Cambrian
    - Lower Palaeozoic
    - Mesozoic
    - Lower Tertiary
  - Sector boundary
  - Coast line
  - Time depth contour  
(values in sec.)
  - Normal fault  
(lines showing dip of fault plane)
  - Reverse fault  
(lines showing dip of fault plane)
  - H High
  - L Low
  - Well
  - Anticline
  - Fault zone
  - Dip direction



N 55° 30'

N 55°

N 54° 30'

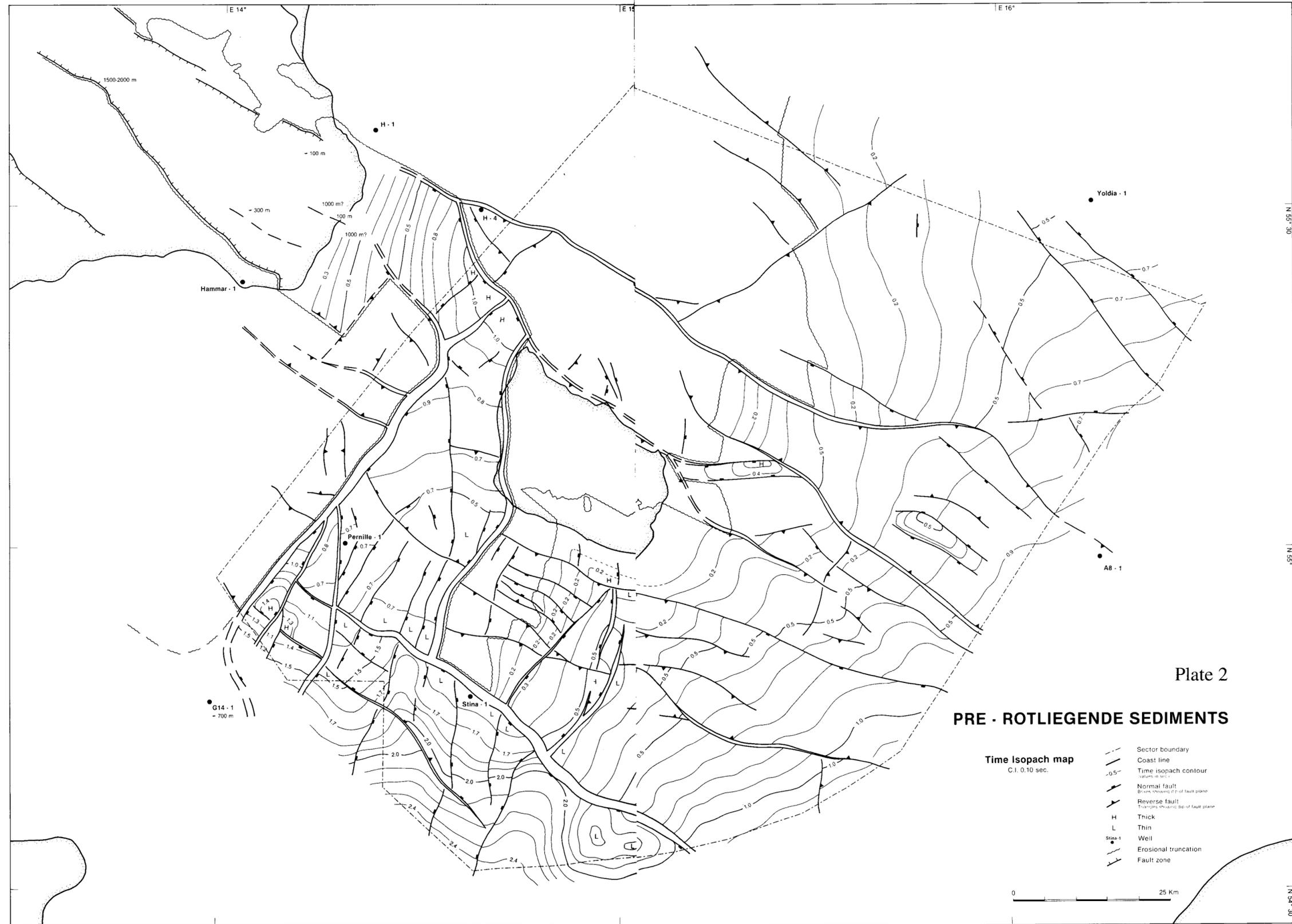


Plate 2

**PRE - ROTLIEGENDE SEDIMENTS**

- Time isopach map**  
C.I. 0.10 sec.
- Sector boundary
  - Coast line
  - Time isopach contour  
value in sec.
  - Normal fault  
Down-throwing dip of fault plane
  - Reverse fault  
Up-throwing dip of fault plane
  - H Thick
  - L Thin
  - Stina-1 Well
  - Erosional truncation
  - Fault zone

0 25 Km

05° 55' N



Plate 1

ROTLIEGENDE

Time Isopach map

C.I. 0.10 sec.

-  Sector boundary
-  Coast line
-  TWT - contour
-  Normal fault  
Boxes showing dip of fault plane
-  Reverse fault  
Triangles showing dip of fault plane
-  H Thick
-  L Thin
-  Well
-  Erosional truncation

0 25 Km

**This paper provides an account of the hydrocarbon prospectivity of the Palaeozoic of the Bornholm area. Basin modelling and reconstruction of Palaeozoic basin geometry illustrates important points in the geological development relevant for Palaeozoic source rock maturation. The presentation includes a review of the main structural elements and the Palaeozoic stratigraphy. Maps of seismic key horizons relevant for the Palaeozoic are included.**