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ABSTRACT

Hanöbuktens berggrund har undersökts med reflektions-seismiska metoder. Undersökningen omfattar området öster om Skåne fram till en linje söderut från Öland.

Hanöbukten indelas geologiskt i fyra delområden med olika geologisk och tektonisk utveckling. Dessa enheter är: 1) Den sydligt sluttande "Hanö Bay slope" som utgör den direkta fortsättingen av Blekinges kustslätt. 2) Den östligt stupande "Kalmarsund slope", som söder om Öland utgör den västra delen av den paleozoiska Baltiska sänkan. 3) Den mesozoiska "Hanö Bay halfgraben", som omfattar de centrala och södra delarna av Hanöbukten. Den pågående sänkningen av detta område beräknas till ca. 20-60 m under kvartär tid. 4) Den deformerade berggrundsenheten "Yoldia structural element", som utgör ett avskilt paleoziskt berggrundsblock som utsatts för förkastningsrörelser och möjligen rotation. Detta berggrundsblock är beläget öster om enhet 3.

Den sedimentära utvecklingen i Hanöbukten efter paleozoikum domineras av två tektoniska faser, nämligen: 1) Den tidigt kimmeriska fasen, som omfattar tre tektoniska pulser under i huvudsak jura och som ledde till en aktivering av de redan initierade förkastningssystemen och insjunkningarna samt en begynnande sedimenation inom "Hanö Bay halfgraben". 2) Den tektoniska fasen i sen krita, som utgör den viktigaste fasen för utvecklingen i "Hanö Bay halfgraben" och under vilken huvuddelen av sedimentationen och insjunkningen skedde. Denna senare fas ledde vidare till kompressionsrörelser utmed Tornquist-zones huvudaxel.

Förkastningsystemen i Hanöbukten domineras av tre huvudriktningar i NV-SO, NO-SV och VNV-OSO. De två dominerande tektoniska elementen i området är "Kullen-Christiansö Ridge system" (NV-SO) och "Bornholm Gat tectonic zone" (NO-SV). Dextrala strike-slip rörelser om 2-3 km är indikerade i samband med de tektoniska rörelsena under senare delen av krita. Hanöbuktens södra delar är indikerade att genomgå en aktiv insjunkning som troligen har pågått alltsedan prekvartär tid.

ABSTRACT

The tectonic framework and the general geologic development of the Hanö Bay, from the Scanian coast in the west to south of Öland in the east, has been investigated by means of reflection seismic methods. The Hanö Bay is in this paper subdivided into four areas of different geologic settings. These are: 1) The Hanö Bay slope, which forms a southward dipping continuation of the rigid Blekinge coastal plain. 2) The eastward dipping Kalmarsund Slope, which southwards from Öland forms the western part of the Paleozoic Baltic Syneclise. 3) The Mesozoic Hanö Bay Halfgraben, which forms the central and southern parts of the Hanö Bay. The ongoing subsidence of the Halfgraben is estimated to be in the order of 20-60 m during the Quaternary. 4) The Yoldia Structural Element, which forms a deformed, tilted and possibly rotated block of Paleozoic bedrock located east of the Hanö Bay Halfgraben. Two tectonic phases dominate the post-Paleozoic development of the Hanö Bay, these are: 1) The Early Kimmerian phase, which initiated subsidence and reactivated older faults. 2) The Late Cretaceous phase, which is the main subsidence phase of the Hanö Bay Halfgraben. The tectonic fault pattern of the Hanö Bay is dominated by three directions, i.e. NW-SE, NE-SW and WNW-ESE. The two main tectonic elements of the area are the Kullen-Christiansö Ridge System (NW-SE) and the Bornholm Gat Tectonic Zone (NE-SW). Sinistral strike-slip movements in order of 2-3 km are interpreted to have occurred along the Bornholm Gat Tectonic Zone during the Late Cretaceous.

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SUMMARY

This paper deals primarily with the post-Paleozoic tectonic development of the Hanö Bay and the geodynamic relation of this area to the Tornquist Zone. The tectonic framework and structural outline presented are based on seismic stratigraphy, and therefore no absolute timing of the separate tectonic events is possible. However, a special emphasis has been made to separate post-Tertiary (neotectonic) movements from older tectonic phases.

The results presented in this paper are largely obtained from single channel seismic reflection profiles recorded during the period 1975-1982. This seismic data set contains about 5000 km of seismic reflection profiles in the Hanö Bay displayed in 0.5 s. TWT. Two additional seismic data sets, used for this paper, contain about 1200 km of unmigrated multi-channel seismic reflection profiles displayed normally in 2-3 s. TWT. These latter data sets were recorded by Oljeprospektering AB (OPAB) between 1971 and 1973 and by Dansk Boreselskab AS between 1975 and 1976.

The Hanö Bay is located offshore southeastern Sweden along the southwestern border of the East European Platform. The sedimentary bedrock ranges in age from Early Paleozoic to Late Cretaceous. No Tertiary sedimentary deposits have been subdivided in the Bay, although minor remnants may be present. The Quaternary sediment cover includes deposits from at least two glaciations followed by post-glacial clays and muds. The seabed is to a large extent depositional.

The Hanö Bay has been subdivided into four areas of different geological settings, namely:

1) The Hanö Bay slope, which forms the southward dipping continuation of the rigid Blekinge coastal plain. The area forms an almost undeformed sub-Mesozoic peneplain covered by thin Mesozoic strata.

2) The eastward dipping Kalmarsund Slope, which forms the western part of the Paleozoic Baltic Syneclise. The Kalmarsund Slope comprises the Kalmarsund and Öland area, and southeastwards. It is separated from the Baltic Syneclise in the east by a NNE trending hinge zone passing closely east of Öland. The Slope has a general ESE basement dip, and is covered by Cambro-Ordovician sedimentary strata. Tectonically, this area was to a large extent developed already during the Paleozoic,

opposite to the Hanö Bay Halfgraben which has a SSW dip and which seems to have developed during a major subsidence phase in the Late Mesozoic.

3) The Hanö Bay Halfgraben, which forms the central and southern parts of the Hanö Bay. It is a tectonically formed halfgraben initiated in the Triassic but mainly developed during the Late Cretaceous. The Halfgraben is infilled by a Late Triassic to Quaternary sequence on top of local remnants of possible Lower Paleozoic strata. To the north the Halfgraben is separated from the Hanö Bay Slope by the approximately E-W trending Hanö Bay Flexure, and to the south it is terminated by the Kullen-Christiansö Ridge System. This Ridge System, which is a 250 km long structural feature, excluding its northwestward prolongation into the Danish Basin, is considered to be the most important structural feature for the development of the Hanö Bay Halfgraben. Vertical movements in the order of 1000 m have occurred along the NE side of this Ridge. The subsidence of the Halfgraben seems to continue throughout the Quaternary and is still indicated to be active. The glacial and postglacial subsidence is estimated to be in the order of 20-60 m, although the isostatic effects of loading and unloading of the ice caps during the Quaternary have not been possible to estimate. This subsidence could also explain the neotectonic faults related to the Halfgraben.

4) The Yoldia Structural Element, which forms a deformed, tilted and possibly rotated block of Paleozoic bedrock. This Element, which has its name after an offshore boring, is located at the eastern edge of the Hanö Bay Halfgraben. The Yoldia Structural Element indicates a strong tectonic influence after that the sub-Mesozoic peneplain was developed in the Hanö Bay. The Paleozoic stratal sequence is uplifted, tilted and faulted here, quite opposite to the conditions within the surrounding very even sub-Mesozoic peneplain area.

The Bornholm Gat forms a separate tectonic element outside of the Hanö Bay. The development of the Gat is closely related to that of the Hanö Bay, and the area must therefore not be left out of the present discussion. The Gat, is dominated by two intersecting tectonic directions. These are the NW-SE direction, which represents the Tornquist Zone, and the NE-SW direction which is a reactivated Precambrian direction. The latter direction was active during the Late Cretaceous compressional phase leading to inversion tectonics in the Gat and associated movements far into the Hanö Bay. Thus, dextral strike-slip movements of this direction have affected the development of the major part of the Hanö Bay area.

1 INTRODUCTION

The present area of investigation is located offshore southeastern Sweden along the southwestern border of the East European Platform (Fig. 1-1). The investigated area extends from the Bornholm Gat in the southwest to south of Öland in the northeast and includes sedimentary bedrock sequences ranging in age from Early Paleozoic to Late Cretaceous and, possibly, Tertiary. The Quaternary sediment cover includes deposits from at least two glaciations followed by Postglacial clays and muds. The seabed is largely depositional.

This paper deals primarily with the tectonic framework of the area with special emphasis on Cretaceous to post-Tertiary movements. The investigation is based on reflection seismic profiles of two kinds, single channel shallow seismics of high resolution and multi-channel deep seismics of moderate to low resolution. The single channel seismic recordings proved to be superior for the purpose of this investigation.

The subject of this investigation was to identify fault movements, both vertical and lateral, in the seismic profiles and if possible to identify the tectonic events related to them. A second subject

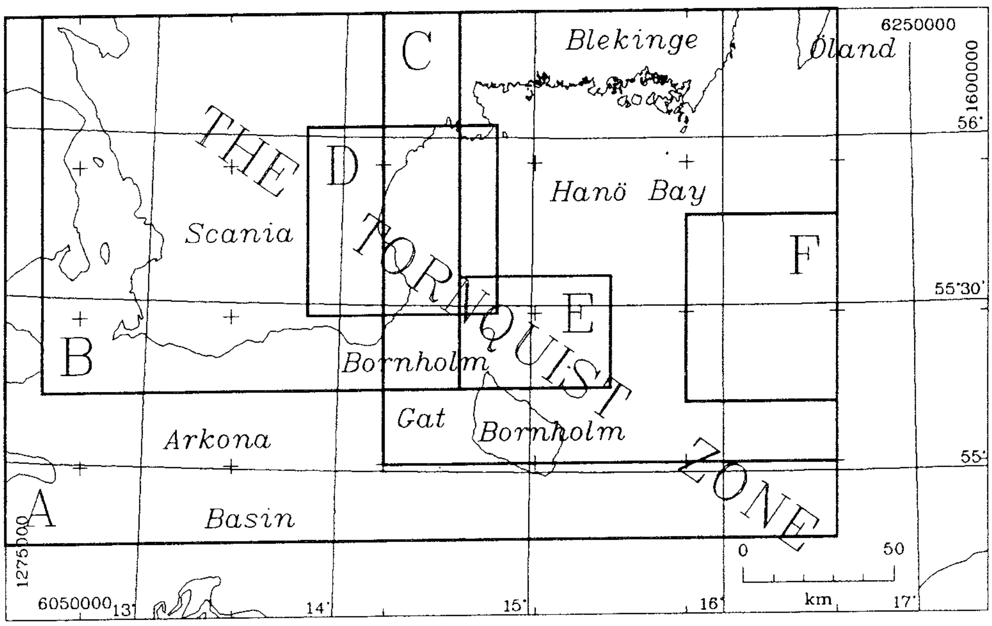

Fig. 1-1 Area of investigation with the location of the tectonic map Fig. 5-2 (A) and of the detail maps Fig. 3-1 (B), Fig. 5-1 (C), Fig.6-1 (D), Fig. 6-3 (E) and Fig. 6-7 (F).

was to investigate the influence of late tectonic (neotectonic) movements on the Tornquist Zone and in the Hanö Bay. The investigation also attempts to demonstrate the use of marine seismic methods for interpretation of recent movements.

In a wide sense, the investigated area belongs to the Tornquist Zone, although in the south Baltic Sea the Zone is more often associated with the location of the Christiansö and Bornholm horst systems. Within its generally accepted limits, the Tornquist Zone extends approximately from the Black Sea in the southeast to the North Sea in the northwest. It is the major tectonic zone of the southern Baltic Sea. The Zone, which in parts has an origin as a Precambrian rift zone, and a subsequent history as an Early Paleozoic plate boundary, has been recurrently reactivated during several Late Paleozoic and Mesozoic orogenic phases. Today it forms the instable boundary between the East European Platform and the Central European Plates.

The margin of the East European Platform forms a complex zone of block-faulted Precambrian crystalline basement covered by Early Paleozoic, Mesozoic and Cenozoic sediments of highly variable thicknesses. In the Scandinavian part of the Tornquist Zone, faulting has recurrently occurred from Precambrian into Early Tertiary although different segments have moved independently of one another during geological time. Important tectonic phases are recorded from the Late Silurian-Early Devonian, Permo-Carboniferous, Late Triassic-Jurassic and Cretaceous-Paleogene. The Tornquist Zone is interpreted be active until present time.

The most important faults along the Baltic Sea part of the Tornquist Zone trend NW-SE, which is along the main direction of the Zone. Other fault trends of importance for the development of the Zone are the N-S to NE-SW directions. These latter directions often create structural elements perpendicular to the general direction of the Tornquist Zone.

2 METHODS AND MATERIAL

The results presented in this paper are mainly obtained from single channel seismic reflection profiles recorded by the Department of Geology and Geochemistry, Stockholm University, during the period 1975-1982. This seismic data set contains about 5000 km of seismic reflection profiles displayed in 0.5 sec. TWT. A second seismic data set used for this paper contains about 1000 km of unmigrated multi-channel seismic reflection profiles displayed normally in 2 sec TWT. These profiles were recorded by Oljeprospektering AB (OPAB) in the years 1971-73. A third data set, which was consulted for the Danish part of the Hanö Bay, contains about 200 km of unmigrated multi-channel seismic reflection profiles displayed in 3 sec TWT. These profiles were recorded by Dansk Borselskab AS in the years 1975-76.

The tectonic framework of Scania as shown in Fig. 5-2 is based on the bedrock geology map of Scania (SGU Ser. BA 43). The tectonic pattern of the Blekinge county is compiled from several maps of bedrock geology and hydrogeology of the area.

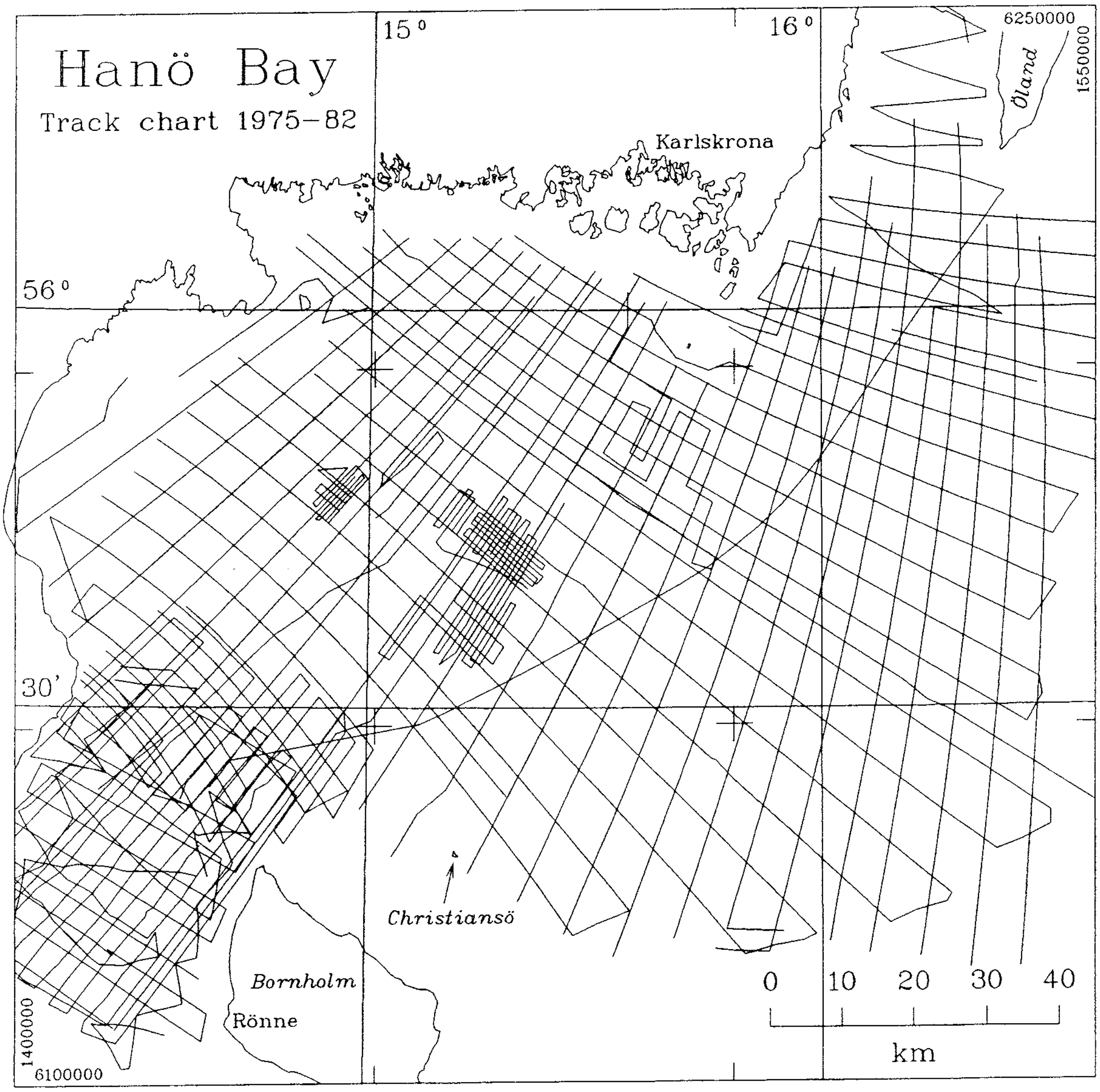

Fig. 2-1. Location of single channel seismic lines shot during the period 1975 to 1982.

2.0.1 Methods of investigation. The results presented in this paper are mainly based on echosoundings and single channel seismic reflection profiling. A comprehensive description of the instrumentation used for this, and also other, marine seismic surveys in the Baltic is given by Flodén (1981) and therefore, only a brief presentation of the geophysical instrumentation is given here. For general descriptions of the geophysical methods on hand, single channel as well as multichannel, reference is made to Hersey (1963).

Navigation. The Decca Navigator System, South Baltic Chain (0A), was used for the present investigations. The Decca System is a radio navigational system producing a hyperbolic grid pattern of navigational lines across its coverage area. It contains several local chains around Sweden, each covering a specific sea area with a fixed hyperbolic grid.

In the Hanö Bay, the positional accuracy, during daytime and under favourable meteorological conditions, is estimated to be in the order of +/- 50 m. During echosounding and seismic reflection profiling, position fixes were taken every twenty minutes along the survey lines and additionally when changing course, or cruising speed. The cruising speed was generally around 7 knots.

Echosounding and reflection profiling. Simultaneous echosounding and seismic reflection profiling were performed along pre-determined lines coincident either with the NE-SW "green" or the NW-SE "red" Decca Lanes in the Hanö Bay.

A 30 kHz echosounder was used to measure water depth and to achieve information on the topmost postglacial seabed sediments. During 1982 a mud-penetrator sounder at 4 kHz was used to obtain high resolution profiles of the glacial and postglacial clayey sediments and to determine the boundaries to subjacent glacial drift or bedrock.

An analogue, single-channel, seismic reflection profiler was used to obtain information on the sedimentary bedrock. In general, the information achieved by this method is a compromise between penetration and resolution (Hersey 1963). In the Hanö Bay the sedimentary bedrock is poorly consolidated and has generally low sound propagation velocities (around 2000 m/s). Therefore, unusually deep penetrations could be achieved, in some profiles more than 700 m.

A PAR-600B airgun was used as seismic transmitter. Its firing chamber of 320 cm3 was equipped with a pulse shaping unit, which effectively extinguished the disturbing bubble pulse. The reflected signals were received by a 50 element hydrophone streamer. Amplified, but unfiltered, signals were recorded on magnetic tape and simultaneously the selected band-pass was recorded on a precision graphic recorder. At sea, the single-channel reflection seismic profiles were filtered and displayed either at 100-200 Hz (1975-80) or at 250-500 Hz (1981-82), the graphically displayed time interval was 0.5 s. Selected parts of the magnetic tapes were later replayed with various filter settings in order to obtain additional information.

2.0.2 Horizontal and vertical scaling in seismic profiles. The vertical time scaling in the present single channel seismic profiles is fixed and independant of sound velocities etc. The horizontal scaling, on the other hand, is dependent on variations in the ship's speed. Thus, the horizontal distance in the seismic profiles is facilitated by successive position markings. The present marker interval was 20 minutes between position fixes which equals to a horizontal distance of about 4.5 km. The vertical scaling in the profiles is facilitated by the constant stylus speed across the recording paper. Horizontal lines, normally spaced 25 ms (milliseconds) apart were printed in addition to the seismic information. It should be observed that 25 ms is the two way travel time of the seismic signal equalling to about 18 metres at water velocity.

2.0.3 Quality of data. The multi-channel recordings have been used to delineate major tectonic blocks and major vertical structures, as e.g. ridges, whereas the high resolution single channel recordings were used to distinguish more delicate structures, as e.g. faults of moderate or low vertical offset. It should be noted that the rather old multi-channel recordings used for this study lack the detailed structures normally found in modern recordings.

2.1 DEFINITIONS OF FAULTS

Fault, is a neutral term that is neither related to the size of a structure or to any displacement value. The displacement along a fault may be translational or rotational. The relative lateral component of displacement along a fault could be left-lateral (sinistral) or right-lateral (dextral). The faults and the lineament presented in Figs. 2-2 and 2-3 show the "normal" outline which separates the three categories used i the paper. The term sedimentary fault, or normal fault, is here used for pre-Quaternary movements in the sedimentary bedrock.

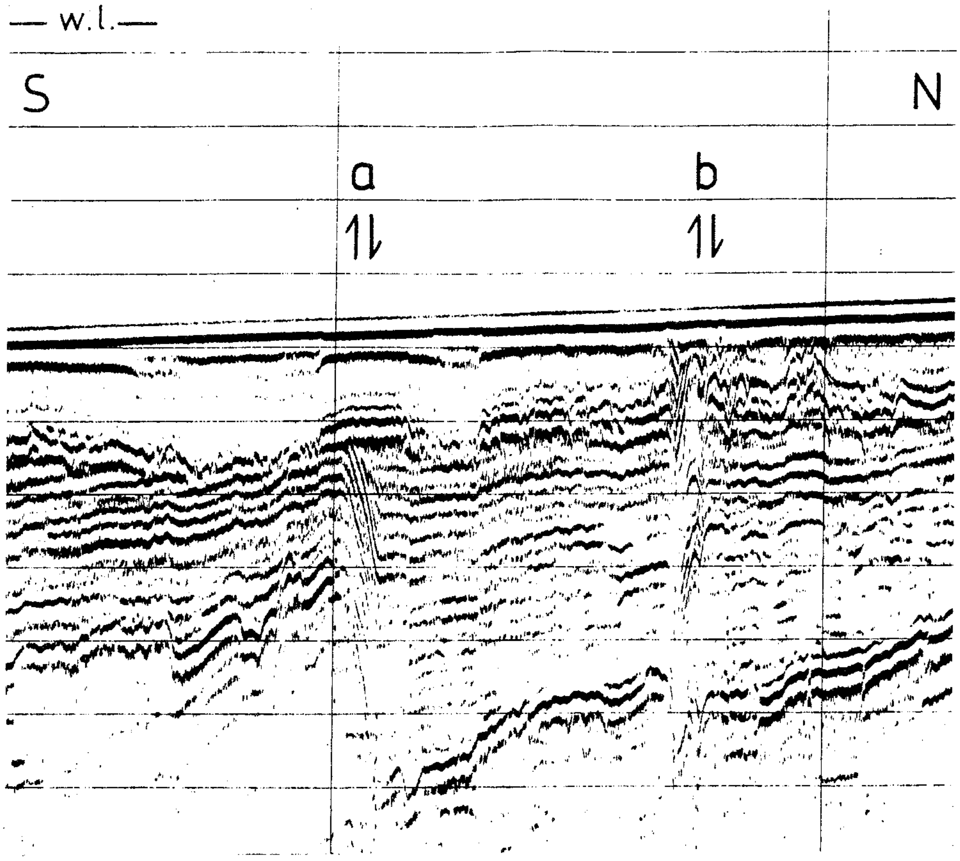

Fig. 2-2 Single channel seismic profile with examples of a) sedimentary fault and b) neotectonic fault. Horizontal and vertical scales are described on p. 5. Location of profile is marked 6 in Fig. 5-2.

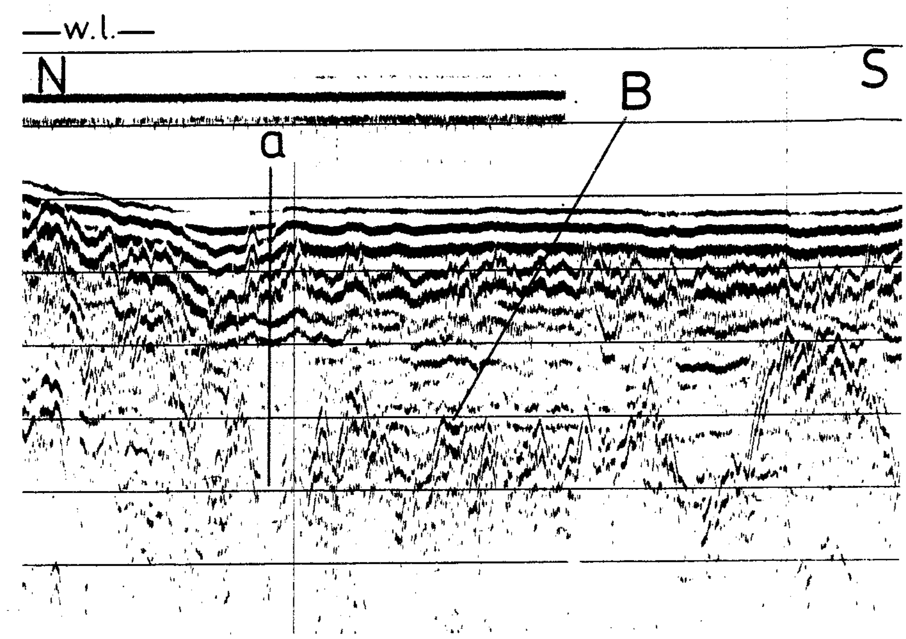

Fig. 2-3 Single channel seismic profile demonstrating the basement relief along the Hanö Bay Slope (B) and a fracture valley (a), classified as a lineament in this paper. Horizontal and vertical scales are described on p. 5. Location of profile is marked 5 in Fig. 5-2.

The term neotectonic fault is in this paper used to describe a vertical or lateral offset caused by one or more of three agents in different combinations, namely; lateral movements, subsidence and sediment loading. The term neotectonic fault refers to post-Tertiary movements in the sedimentary column.

In the northern part of the Hanö Bay the term lineament is used. It is a mappable composite linear feature in a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and reflects a subsurface phenomenon.

In order to fully evaluate the lineaments which traverse the Hanö Bay Slope, a very time consuming procedure must be made. Thus, the seismic profiles must be entered into a computer system in order to produce an accurate isoline map of the basement relief. No such efforts have been made in the present investigation.

The grid of the seismic lines in the Hanö Bay are orientated in NW-SE and NNE-SSW directions and separated at least 5 km apart. This means that only faults of a regional extension are presented. Faults of short extension can be identified in the seismic records, but their strike remains unknown and they are therefore not included in the present maps.

We naturally acknowledge that faults in areas covered by sedimentary bedrocks do not have the straight rectilinear outline presented in the present tectonic maps of the Hanö Bay. Normally the faults are much more curvated, but due to the large spacing between the seismic lines, we have decided to present the tectonic pattern in the present outline.

3 GENERAL GEOLOGY AND TECTONIC OUTLINE OF THE BALTIC SEA SECTOR OF THE TORNQUIST ZONE

The sedimentary cover of the Baltic Sea is dominated by Paleozoic sequences (Figs. 3-1 and 3-2). Southwest of a line between the Hanö Bay in the NW and Lithuania in the SE, the border area of the East European Platform is covered by Mesozoic sequences resting partly on unevenly deep eroded Paleozoic sedimentary rocks and partly on the crystalline basement. Mesozoic and Tertiary rocks cover the boundary to the Central European Plates

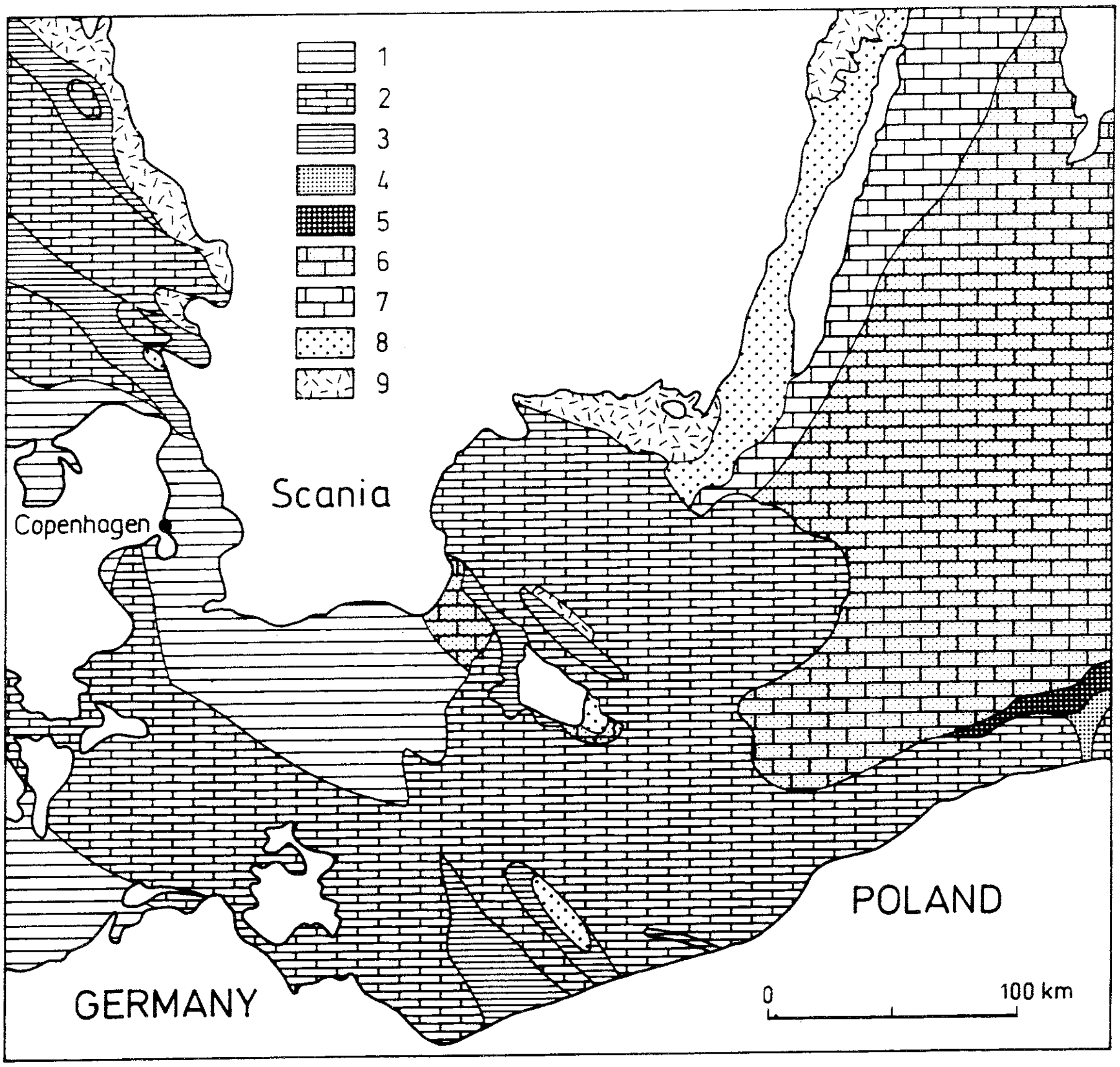

Fig. 3-1 General Pre-Quaternary geology of the southern Baltic Sea. Legend: 1 - Tertiary, 2 - Cretaceous, 3 - Jurassic, 4 - Triassic, 5 - Permian, 6 - Silurian, 7 - Ordovician, 8 - Cambrian, 9 - Undifferentiated crystalline bedrock.

in the general trend from Scania to Poland. The Tornquist Zone (Fig. 3-3) forms a 30-50 km wide zone along the platform boundary, including within its limits the tectonically mobile parts of the Platform boundary. The northeast boundary of the Tornquist Zone follows approximately the Kullen-Christiansö Ridge, although the Hanö Bay is closely related to the Zone, too.

The tectonic framework of the Baltic Syneclise in the eastern part of the Baltic Sea is mainly a result of Paleozoic orogenies and related movements. The uplift of the Scandinavian mountain chain during the Caledonian orogeny resulted in rotation of basement blocks and a general elevation

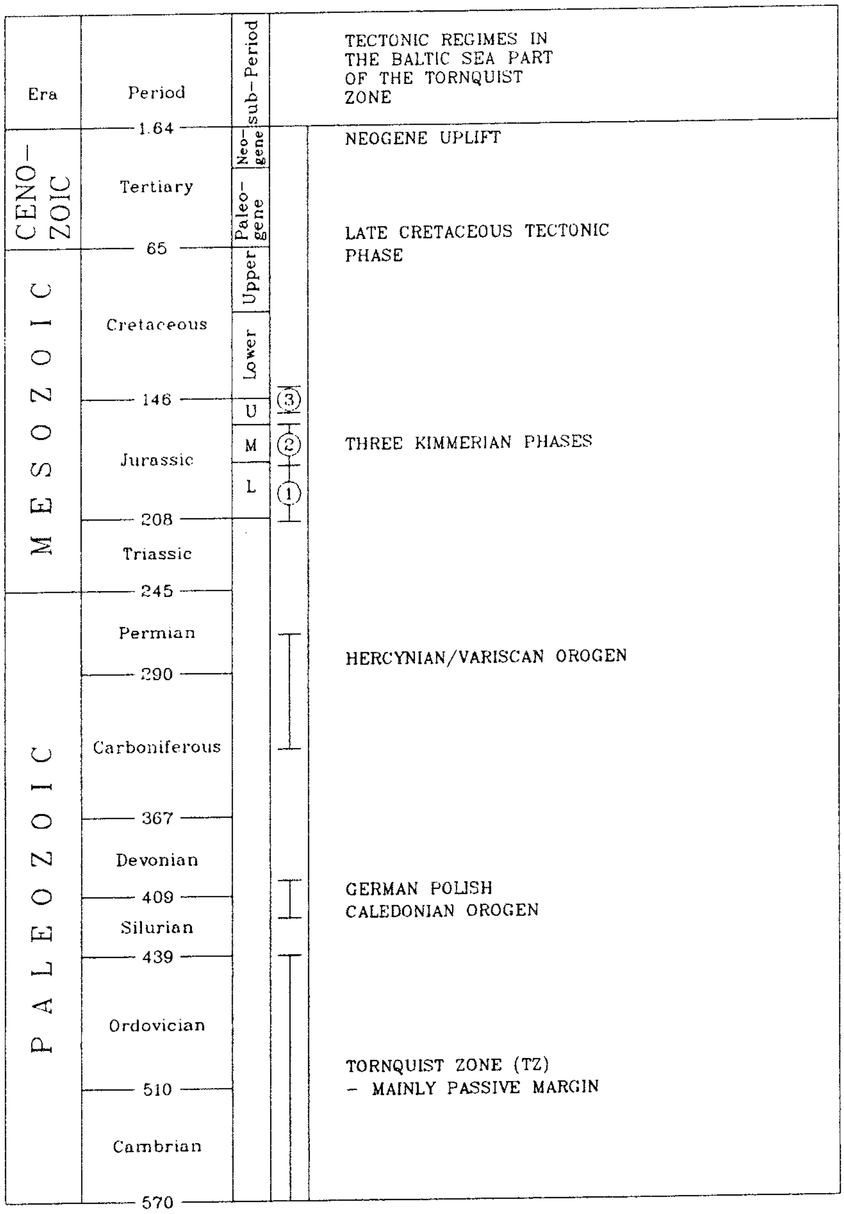

Fig. 3-2 Stratigraphy and tectonic regimes.

of the basement in the Baltic Sea. Thus, the first tectonic pulse to affect the Tornquist Zone during the Paleozoic was time related to the Caledonian Orogeny. This geodynamic development is here tentatively subdivided into two different phases. The first phase in the Late Silurian is characterized by a tensional regime, quite opposite to the compressional regime along the Caledonian front in between Laurentia and Baltica (Fig. 3-2). The second phase developed a compressional regime at the transition between the Silurian and the Devonian; it is generally known as the German-Polish Caledonian deformation front. This defor-

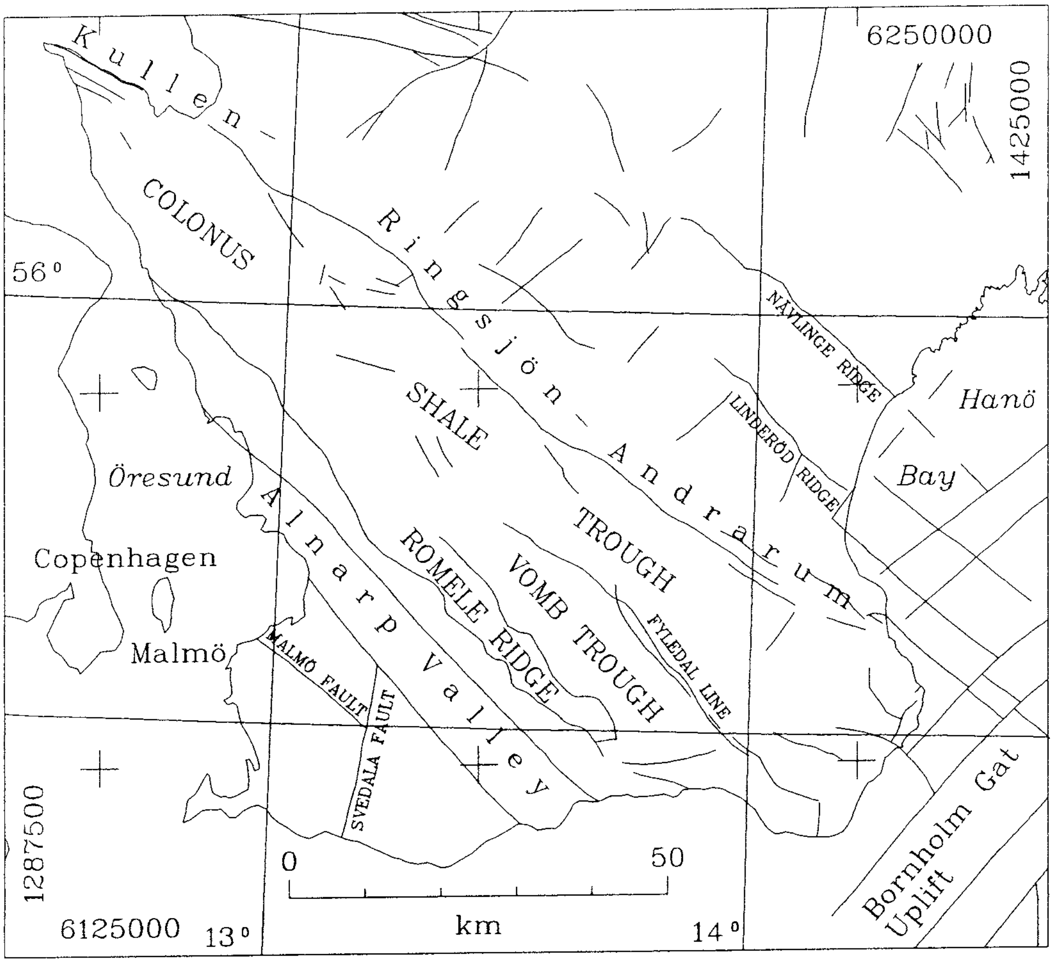

Fig. 3-3 Structural geology of Scania, modified after Norling & Bergström (1987). For location of map, see Fig. 1-1.

mation front coincides with the Tornquist Zone in Poland and extends in a WNW direction across the Baltic Sea. It crosses the Arkona Basin north of Rügen and continues south of the Ringköping-Fyn High in Denmark (Dadlez 1990).

With the exceptions of the Caledonian and Hercynian/ Variscan tectonic phases, the Paleozoic sequence of Scania indicates a quiet platform type of sedimentation with low accumulation rates. The location of Scania in the near proximity of the Platform Border at this time is indicated by about 3000 m of continental slope sediments below Rügen, however. The Caledonian exception from this stable period is recorded by the deposition of the Upper Silurian Colonus Shale in Scania. During a short time interval of rapid sinking in the Ludlowian the Colonus Shale reached a thickness of almost 1000 m (Norling and Bergström 1987). During this period Scania became tilted to the south. In Scania, the

Upper Silurian is preserved in the Colonus Shale Trough extending NW-SE through Scania (Fig. 3-1).

The sedimentation pattern of the Upper Silurian sequence in the central part of the Baltic Syneclise indicates a similar period of active sinking in the Pridolian (latest Silurian), i.e. somewhat later than in Scania. A regional dip towards the SSE within the Syneclise is shown by a major increase in thickness of the Pridolian from Gotland to Estonia and southwards.

Contrary to the Scanian area, the Paleozoic sediments show rapidly increasing thicknesses to the east and south along the Baltic Sea part of the Tornquist Zone. The present day distribution of thick Paleozoic sediments is, however, mainly a result of Late Paleozoic erosion and later tectonic phases. The strata are truncated by a major unconformity, corresponding to the base of late Permian, or Mesozoic, sediments. The Mesozoic sediments are primarily restricted to tectonic basins along the Tornquist Zone, nowhere in the Baltic region reaching any extensive distance into the East European Platform.

The Hercynian/Variscan orogeny developed a generally compressional regime along the Tornquist Zone although tensional structures are evident i Scania. During this period, from Early Carboniferous to Late Permian, a wide zone along the SW border of the East European Platform was raised and subjected to wedge-shaped erosion. This resulted in a sub-Mesozoic peneplain which extends across the Baltic Sea from Lithuania in the southeast to southern Sweden in the northwest. In the Hanö Bay and northwards to Småland, the erosion reached the crystalline basement.

With the onset of the Hercynian/Variscan wrench tectonics during the Late Carboniferous to Early Permian, dextral wrench-faulting along the Baltic part of the Tornquist Zone resulted in the uplift of basement blocks (Norling and Bergström, 1987). In Scania this period also resulted in extrusives, the feeder dikes of which are preserved today, further emphasizing the period of extensive erosion preceeding the Early Mesozoic transgression (Bergström et al., 1982).

In the Danish and Polish parts of the Danish-Polish Trough evidence point towards a tectonic reactivation during the Late Permian. This reactivation is followed by rapidly subsiding basins in Denmark and Poland during the Triassic.

The tectonic activation and subsequent sedimentation in the Hanö Bay Halfgraben during Triassic is possibly somewhat younger. Thus, a Triassic reactivation of the Kullen-Ringsjön-Andrarum dislocation zone (Norling & Bergström 1987), which extends southeastwards into the Christiansö Ridge System, points towards a Late Triassic development of the Hanö Bay Halfgraben. This is also supported by the fact that the oldest sedimentary bedrock in the offshore borings in the SW part of the Hanö Bay is interpreted to be of a Late Triassic age (Norling & Bergström 1987).

During the Mesozoic rifting phases, which are generally recognized to start with the onset of the first of the three Kimmerian phases during the Late Triassic, the Tornquist Zone became repeatedly reactivated, normally under transtensional stress regimes.

The Early Kimmerian movements in Rhaetian (Late Triassic) time are characterised by a slight regional westward down-warping of Scania towards the Danish Trough (Bergström et al. 1982). The Rhaetian to Early Jurassic transgression did not permanently affect Scania until Hettangian (Early Jurassic) time, dominated here by continental to deltaic deposits. During later transgressions in the Early Jurassic the tectonic activity increased, basement blocks in Scania were uplifted and the long period of cyclic marine sedimentation was replaced by continental erosion and deposition, which marked the culmination of the Early Kimmerian phase (Norling & Bergström 1987). This period is characterized by rapid variations in stratigraphic representation, lithologies and thicknesses (Bergström et al. 1982).

The Middle Kimmerian tectonic phase in the Middle Jurassic resulted again in major uplifts in Scania, characterized by differential uplift of basement blocks. The uplifted areas were successively eroded. Sedimentation of limnic and brackish deposits continued in narrow basinal areas of northern, western and central Scania and in the Hanö Bay. Simultaneously with this tectonic pulse, an extensive volcanism occurred along NW-SE trending tectonic zones (Norling & Bergström 1987). The tectonic development of this phase continued towards the end of the Middle Jurassic with a new marine transgression over Scania. The differential block uplift of the Tornquist Zone resulted in continental-deltaic sedimentation in shallow depressions separated from higher areas of non-sedimentation or erosion.

The Late Kimmerian phase, during the Late Jurassic to Early Cretaceous, resulted an extensive tectonic activity in Scania with movements along pre-existing tectonic zones. The Late Jurassic with a mainly uniform regional facies pattern was replaced at the end of the Jurassic by a pattern of rapid lateral and vertical changes (Norling & Bergström 1987). This tectonic pulse also resulted in a major unconformity and it is at least in part responsible for the almost vertical tilt of the Jurassic sequences at the Eriksdal exposure in the Vomb Trough (Bölau 1973).

With the Late Cretaceous a new tectonic pattern was introduced during which the Tornquist Zone underwent subsidence. In Scania several basins and troughs were reactivated, as southeast of the Romeleåsen Ridge, the Vomb Trough, the Hanö Bay Halfgraben and the Kristianstad and Båstad Basins. The rapid subsidence lead to thick deposits during the Late Cretaceous in these areas. Inversion tectonics resulted in elevation of structural elements and erosion in Scania. The Romeleåsen Ridge, and its continuation into the Danish Basin, was associated with the formation of a giant flexure along its axis (Norling & Bergström 1987). The Late Cretaceous sedimentary pattern was later influenced by inversion movements related to the Alpine (Laramid) tectonic phase, its resulting transpressional field, with a strike-slip component along the NW-SE fault system in the Bornholm Gat.

The tectonic development of the structural elements in the Tornquist Zone during the three Kimmerian phases, combined by eustatic sea-level changes, are the main feature controlling the sedimentary development.

4 TECTONIC FRAMEWORK OF THE BORNHOLM GAT

The Bornholm Gat is located at the intersection of two major tectonic zones in the Baltic Sea, namely the Tornquist Zone and the Bornholm Gat Tectonic Zone. The Tornquist Zone separates the East European Platform to the northeast from the Central European Platforms in the southwest, it extends across Scania as a raised and strongly faulted NW-SE trending zone. The Bornholm Gat Tectonic Zone is one of the NE-SW trending fault systems which subdivide the Bornholm Gat and the Arkona Basin into basinal areas and structural highs.

The Tornquist Zone is traversed by at least four NE-SW trending faults related to the Bornholm Gat Tectonic Zone. The implication of a connection to the Alpine Foreland is not fully evaluated and therefore a local name is suggested for the Baltic part of the zone, namely the Bornholm Gat Tectonic Zone.

This NE-SW Precambrian direction, which has been active through several tectonic phases, is one of the most important trends in the present time tectonic framework of the Baltic Sea. The faults of this direction seem to have acted as strike-slip faults which have been reactivated as late as during the Alpine orogeny (Laramide phase). The strike-slip movements, and the related inversion tectonics, in the Bornholm Gat had a major influence on the present tectonic outline of the Gat. The Laramide transpressional regime also affected the tectonic outline of the Hanö Bay in general.

The sedimentary bedrock sequences of the Bornholm Gat are closely related to those onshore in Scania and on Bornholm. Bornholm Island consists of Precambrian crystalline rocks possibly related to the Blekinge Province. The crystalline rocks are covered in the southwestern and southern parts of Mesozoic and Paleozoic sedimentary rocks. The sedimentary bedrock of Scania is of Paleozoic age along the southeastern coast towards the Bornholm Gat. The Mesozoic sequences in the Bornholm Gat are preserved between structural highs, the strata are dominated by Triassic to Cretaceous sediments.

The northern part of the Bornholm Gat is the most complex part of the investigated area. Its tectonic development is only described in general terms in this paper. The Kullen-Christiansö Ridge System, which is built up of the system of basement blocks described on pp. 24-31, delimits the Hanö Bay Halfgraben from the Bornholm Gat structural element. The northern Bornholm Gat is traversed by NE-SW trending strike-slip faults, which divide the Ridge System into several small basement blocks.

The N-S orientated Rönne Graben continues in a series of basins towards Poland. It is in its northern part developed between two structural highs: the crystalline complex of Bornholm Island and the Southern Bornholm High to the east and the Bornholm Gat Uplift to the west.

The Rönne Graben seems to have another origin than the typical grabens, as e.g. the Vomb Trough in Scania, along the Swedish part of the Tornquist Zone. These latter grabens are typically rather shallow (around 1000 m) and filled mainly with Mesozoic strata, whereas the Rönne Graben is more than twice as deep and includes considerable thicknesses of Paleozoic strata below the Mesozoic.

The Rönne Graben is interpreted by Liboriussen et al. (1987) as a Permo-Carboniferous pull-apart basin, which developed due to lateral movements causing en enchelon, dextral wrench faulting. The development of the Rönne Graben is considered by us to be more complex. The Graben may well have been initiated already in the Paleozoic due to lateral movements caused by the Caledonian transtensional and transpressional phases. A change in tectonic regime, from transpressional to transtensional, in the Triassic, resulted in a subsidence phase within the Rönne Graben. The rapid Triassic subsidence, and subsequent infilling of thick sediments, described by Liboriussen et al. (1987), point towards a major tectonic phase in the Triassic.

5 TECTONIC FRAMEWORK OF THE HANÖ BAY

The tectonic structures of the Hanö Bay appear to have been developed mainly during the Mesozoic and the Tertiary, although the main part of the structures seem to be rejuvenated and follow pre-existing Precambrian or Palezoic fault directions. The older generations of these structures are extremely difficult to identify in the seismic material because of disturbances by later tectonic orogenies associated with lateral and vertical movements. The post-Paleozoic development has inherited synsedimentary faults, which are still active in the Hanö Bay.

The tectonic elements of the Hanö Bay, identified and discussed in this paper, are; the Kullen-Christiansö Ridge System, the Christiansö Fault, the Bornholm Gat Tectonic Zone, the Hanö Bay Slope, the Hanö Bay Flexure, the Hanö Bay Halfgraben, the Kalmarsund Slope, the Nävlingeåsen and Linderödsåsen Ridges, the Yoldia Fault Zone, and the Yoldia Structural Element (Fig. 5-1).

Evidence of Precambrian influence on the southern Baltic Shield can be seen on Bornholm, where Münter (1973), geophysically defined major fault zones of mainly Precambrian age. Normally, the fault zones have lateral offsets of 600-2500 m, both dextral and sinistral offsets occur. The four dominating directions exhibit a wide variety of trends, viz. NW-SE, N-S, NNE-SSW and NE-SW (Münter 1973). The Precambrian fault directions that dominate the present outline of the Hanö Bay are the NW-SE and NE-SW (Fig. 5-2). These two trends, in addition to a possible Hercynian/Variscan trend of the approximate WNW-ESE direction, dominate the tectonic pattern of the Hanö Bay.

A period of mainly compression in Central Europe during the Late Paleozoic Hercynian/Variscan orogeny resulted in a general uplift of Scania.

Associated with the uplift an extensive erosion of the Paleozoic deposits and the Precambrian basement took place. This erosional phase is also referred to as the Permian-Mesozoic denudation by Lindmar-Bergström (1991). In the Hanö Bay the so called sub-Mesozoic peneplain was developed (Kumpas 1980). Paleozoic rocks are considered by Norling & Bergström (1987) to be absent in the Hanö Bay.

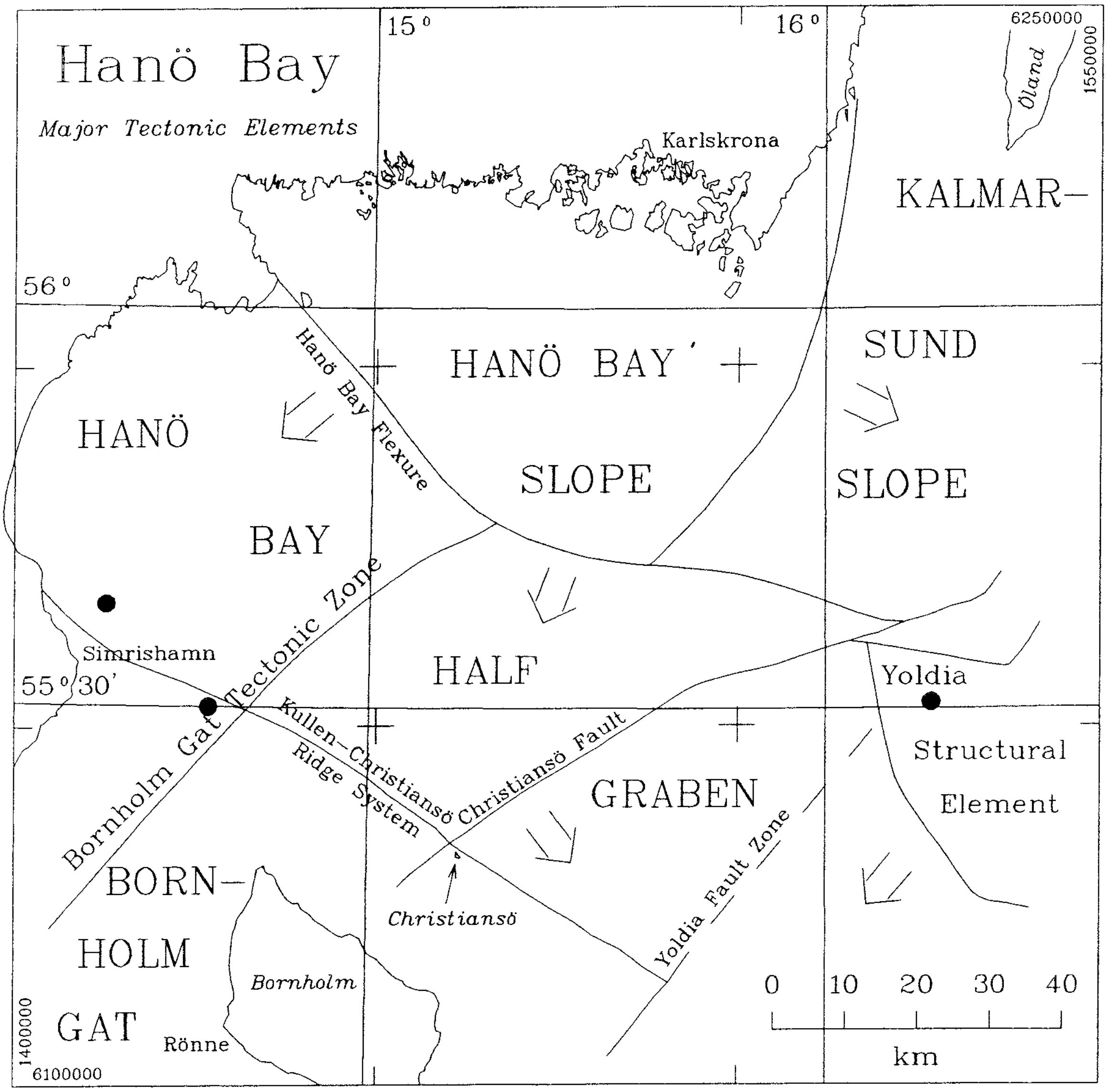

Fig. 5-1 Major tectonic elements and areas of different geological settings. Large arrows indicate the sedimentary dip. The three drilling in the Hanö Bay performed by the Swedish Petroleum Company are marked by dots. For location of map, see Fig. 1-1.

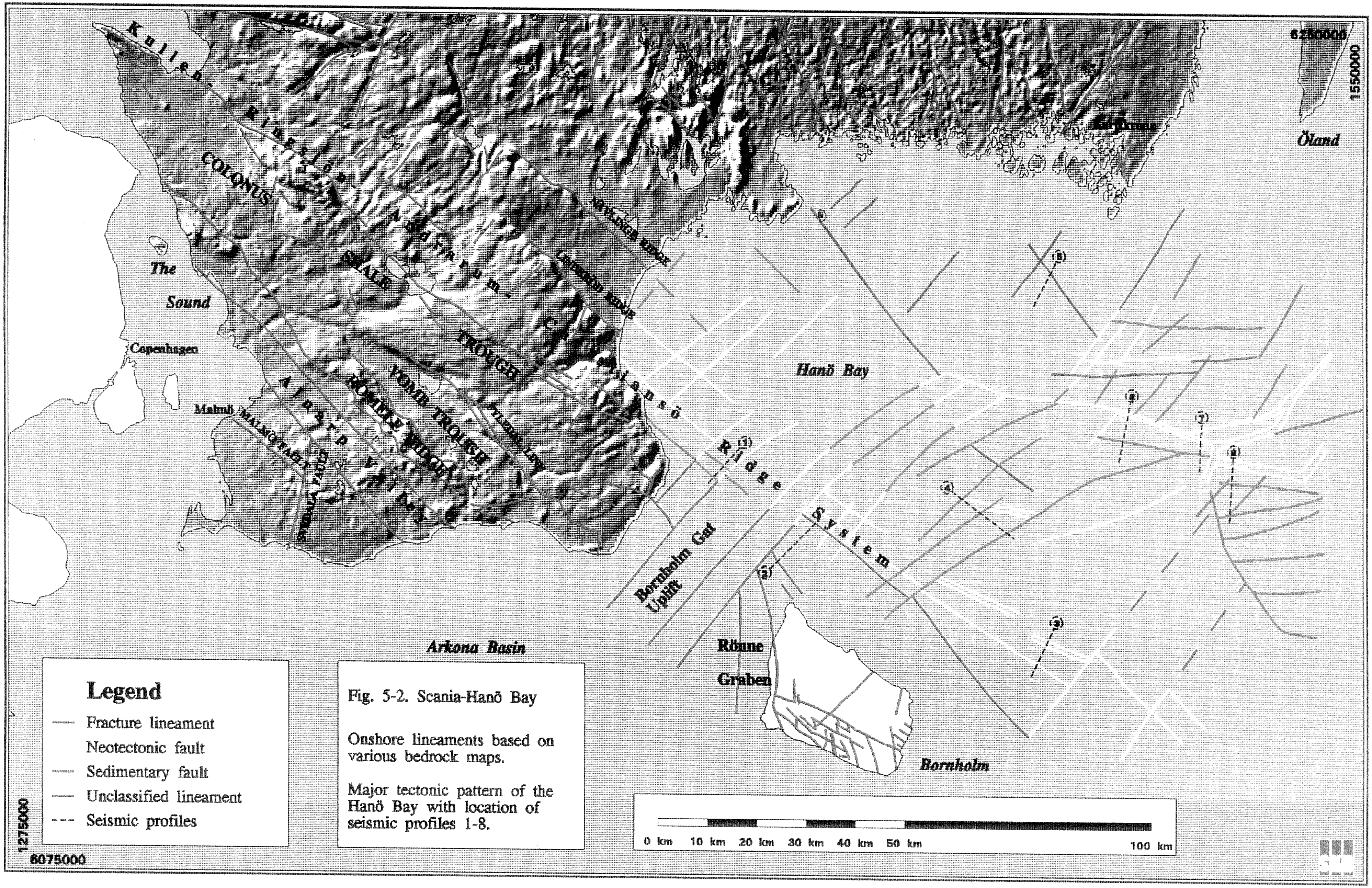

Fig. 5-2. Scania-Hanö Bay

Onshore lineaments based on various bedrock maps.

Major tectonic pattern of the Hanö Bay with location of seismic profiles 1-8.

Thus, a sandstone found in one of the two borings in the Hanö Bay was previously considered to be of Cambrian age. It was later reinterpreted as being of Mesozoic age , presumably Upper Triassic (Norling & Bergström 1987). Thus, the unit below the sub-Mesozoic peneplain previously considered as Cambrian by Kumpas (1980), may be clay-weathered basement rocks (Norling & Bergström 1987). However, seismic refraction velocities measured in the Hanö Bay (Kumpas 1980) and interpretations of multi-channel reflections profiles indicate the presence of a high velocity unit, of a similar velocity range as the Paleozoic of southeast Scania (Wannäs, unpublished material). Paleozoic sedimentary rocks are considered by us to be present at least east of the Christiansö Tectonic Zone and along the Kalmarsund Slope (Fig. 5-1).

The Early Kimmerian tectonic phase initiated a new period of tectonic activity in the Triassic. The rejuvenation and subsidence of the Hanö Bay Halfgraben lead to a transgression of the southern part of the Bay, where Late Triassic sediments were deposited (Kumpas 1980). The two offshore borings in the Hanö Bay, one located to the Kullen-Christiansö Ridge System and the other to the Hanö Bay Half Graben, indicate different tectonic developments in the two areas. The Late Triassic-Jurassic deposits in the Halfgraben indicate a rather rapid and synsedimentary subsidence and tilting towards southwest. At the same time the Bornholm Gat was subjected to erosion, as shown by the hiatus during the Lower to Middle Jurassic (Kumpas 1980).

The Lower Cretaceous up to the Coniancian represents a period of relative low tectonic activity (Kumpas 1980). The Halfgraben is characterized by a slow subsidence without any major tilting of the strata. The next tectonic pulse occurred in the Late Cretaceous (Santonian-Maastrichtian). This pulse involved a rapid subsidence of the Hanö Bay Halfgraben and inversion tectonics in the Bornholm Gat. The pulse conforms with the main subsidence phase of the Halfgraben, where 600-800 metres of post-Coniacian sedimentary bedrock of the total sedimentary thickness of approximatly 1000 metres was deposited (Kumpas 1980). The Late Cretaceous denudation (Lindmar-Bergström 1991) seems to have been restricted to the Hanö Bay Slope. The final tectonic development of the Hanö Bay Halfgraben occurred in post-Maastrichtian (Kumpas 1980).

In a study by Japsen (1992) of the Late Cretaceous and Teriary uplift in northern Denmark, two main types of uplifting movements were considered. One movement comprised the entire area, with increasing uplift towards northeast. The other was related to the Danish part of the Tornquist Zone. These two phases ocurred during the Neogene repectively the Late Createaceous-Paleogen inversion. In the Danish part of the Tornquist Zone the total uplift of the Lower Jurassic varies from 1300 to 1700 metres and the uplift related to the inversion phase is around 750 metres.

Mean sea level registrations during 100 years in the southwestern Baltic region (Striggow & Till 1987), shows that the Tornquist Zone is still active in a subsidence phase. Further indications of active subsidence in the Hanö Bay is discussed on p. 36.

6 RESULTS AND AREAL DESCRIPTION

The Hanö Bay area is here subdivided into four areas of different geological settings, separated and boundered by ridge systems and structural elements (Fig. 5-1).

6.1 THE HANÖ BAY SLOPE

The crystalline basement of the Blekinge Province is exposed in vast areas onland north of the Hanö Bay. The crystalline basement of the Blekinge Province consists to a major part of granites, granitoides and gneisses. The Province comprises the bedrock of the Blekinge County, adjacent parts of eastern Scania and southernmost part of Småland. The Blekinge Province is separated from the Southwest-Swedish Gneiss Province by a N-S trending tectonic zone - the Protogine Zone. The crystalline bedrock of Bornholm, which is exposed over large parts of the island, is interpreted by Johansson & Larsen (1989) to have a similar composition as the Blekinge Province.

The development of the Blekinge Province can be summarised into three rockforming events according to Johansson & Larsen (1989). During the first event, the Tving and Småland granitoids and porphyries was developed, shortly followed by supracrustal units belonging to the Vestanå formation and coastal gneisses around 1800-1700 Ma. The second event formed the Spinkamåla, Karlshamn and Vånga granites around 1400 Ma. The last event resulted in NNE trending dolerites around 950-900 Ma.

The concealed Precambrian basement of the Hanö Bay can be assumed to be of a similar composition to that of the Blekinge Province and Bornholm. No subdivision of the crystalline bedrock can, however, be made from the present reflection seismic profiles. The basement relief of the Hanö Bay Slope is generally 40-60 metres, with a few exceptions up to 120 metres. The irregular relief in the Slope is considered to be due to eroded fracture valleys, which are here classified as lineaments although no vertical offsets are evident.

The Hanö Bay Slope has a low general SSW dip. It is limited to the southwest by the Hanö Bay Flexure, to the south by an E-W segment of the Bornholm Gat Tectonic Zone and to the east by the Kalmarsund Slope.

The main lineament directions along the Hanö Bay Slope are NE-SW and NW-SE although deviations from these directions in the order of 5-15 degrees occur. The lineaments in the Blekinge Province have similar directions, but generally the two directions strike more northerly onshore.

6.2 THE HANÖ BAY HALFGRABEN

The Hanö Bay Halfgraben belongs to the northernmost part of the Tornquist Zone. The basement surface slopes gently towards SSW from the Hanö Bay Flexure (Fig. 5-1), which probably constitutes the northeastern boundary of the Tornquist Zone in the Baltic Sea. The Hanö Bay Flexure is interpreted to have acted as a hinge zone possibly together with the Nävlingeåsen Ridge (the Nävlinge Flexure by Kumpas 1980). The thickest sediments of the Hanö Bay Halfgraben are located to the southern part of the Hanö Bay.

The complex Kullen-Christiansö Ridge System constitutes the southwest border of the Halfgraben. Contemporaneously with movements along the Hanö Bay Flexure, faulting is assumed to have occurred along the northern faults of the Nävlingeåsen and the Linderödsåsen Ridges and along the SE section of the Kullen-Christiansö Ridge System. The Upper Cretaceous dominate the sedimentary column in the two offshore wells drilled along the Kullen-Christiansö Ridge System. The Upper Triassic to Lower Cretaceous stratal sequence in the wells is of moderate thickness, indicating that the main subsidence phase of the Hanö Bay Halfgraben occurred during the Late Cretaceous.

The subsidence phase in the Hanö Bay Halfgraben is proposed to be an ongoing process. The present seismic profiles indicate a subsidence along the northeastern fault of the Christiansö Ridge with a magnitude not less than 60 m during the Quaternary period. No more eloberate datings of the subsidence history of the Hanö Bay Halfgraben can be made from the seismic material, however. This is because of the complicated evolution during the Quaternary period, with vertical oscillations of the crust due to loading and unloading of the ice caps. Lagerlund (1977) suggested Quaternary movements along the northwestern part of the same tectonic system, i.e. the Kullen-Christiansö Ridge System.

6.2.1 The Hanö Bay Flexure. The Hanö Bay Flexure is interpreted to be the major hinge line for the western part of the Hanö Bay Halfgraben. The hinge line is characterised by a change of basement dip, and an increased thickness of the sedimentary rocks in a SSW direction. The zone is partly outlined as a hinge fault, downfaulted in the dip direction. The influence of NE-SW trending faults from the Hanö Bay Halfgraben and lineaments in the Hanö Bay

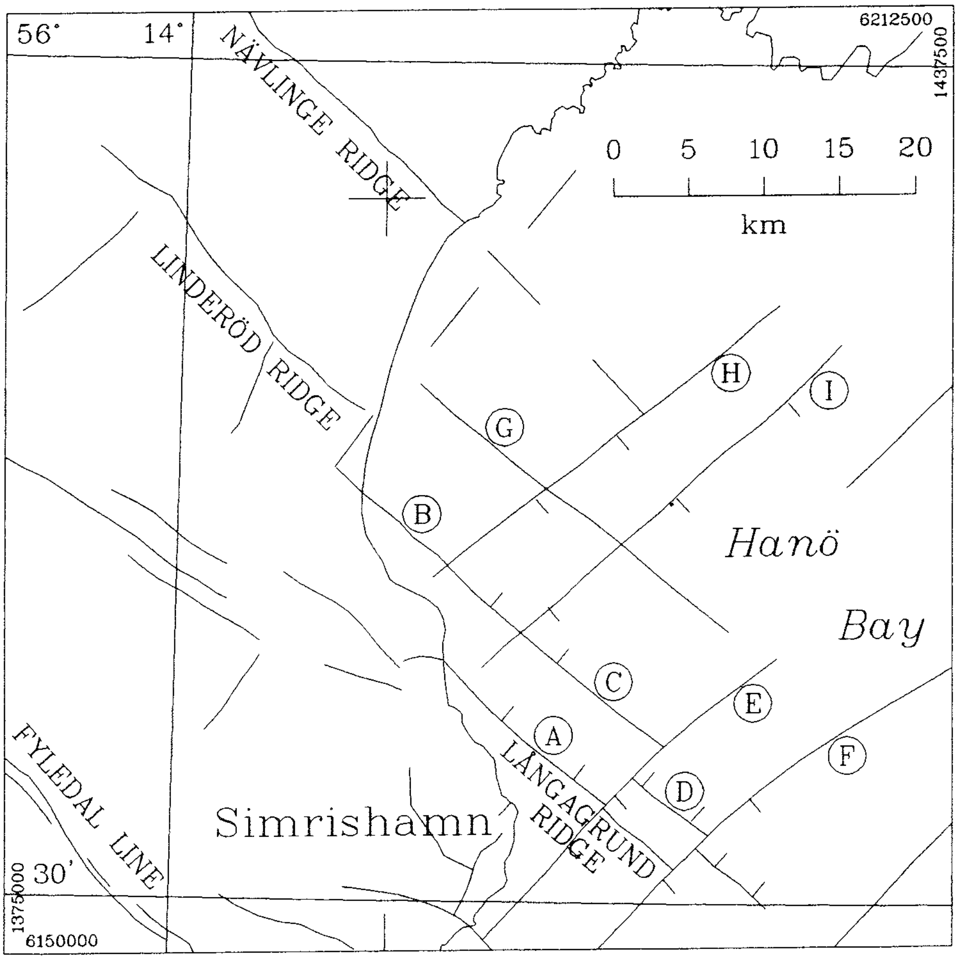

Fig. 6-1 The tectonic pattern of the southwestern Hanö Bay. Faults marked A - I are explained in the text. For location of the map, see Fig. 1-1.

Slope, which are linked or traverse the zone, complicates the interpretation of this tectonic element.

6.2.2 <u>The Nävlingeåsen and Linderödsåsen Ridges</u>. The Nävlingeåsen and Linderödsåsen Ridges, along with other basement horsts in Scania, usually form southwesterly tilted blocks.

The structures are in most cases defined by their northeastern uplifted fault scarps, which have been named the Nävlingeåsen and Linderödsåsen Ridges by Norling & Bergström (1987), Fig. 6-1. The vertical offset of the Nävlingeåsen Ridge is estimated to be around 130 metres onshore (Bergström et al. 1982). An offshore extension of the Nävlingeåsen Ridge named the Nävlinge Flexure, was identified as the axis of a flexure zone in the sub-Mesozoic peneplain by Kumpas (1980). Our reinterpretation of

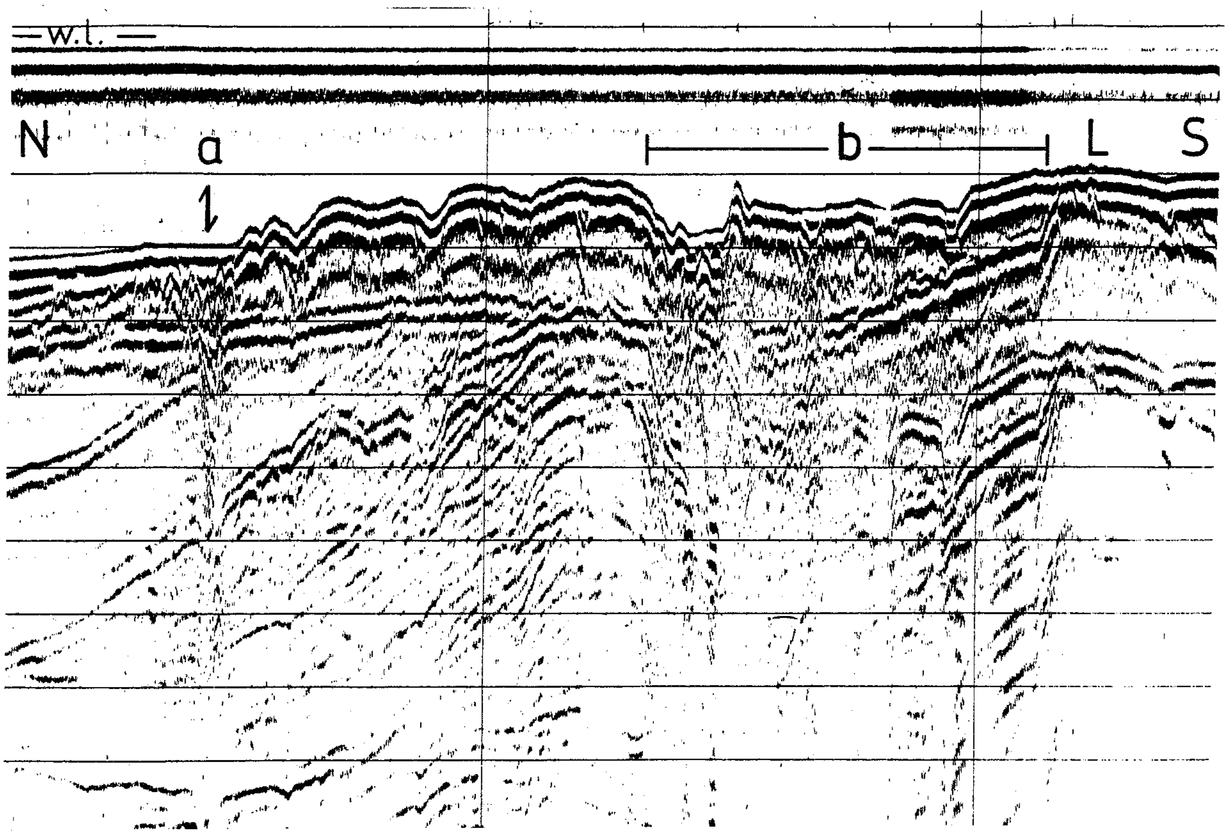

Fig. 6-2 Seismic profile northwards from the Långagrund Ridge (L). The profile displays a) a neotectonic structure and b) the complex fault-zone just north of the Långagrund Ridge. The northern part of the zone (b) is interpreted as the horizontally offset continuation (D in Fig. 6-1) of a sedimentary fault (C in Fig. 6-1), which in the northwest direction converts into a ridge fault scarp (B in Fig. 6-1) associated with the Linderödåsen Ridge. The southern part of the zone (b) is interpreted to coincide with the faults which delimit the Långagrund Ridge towards northeast.

the seismic data shows that the Ridge structure extends as a morphological feature offshore, but also that its trend is cut by the faults H and I (Fig. 6-1), where fault H possibly has acted as a scissor fault. We find no prolongation of the Ridge southeast of these faults. As a matter of fact it is even possible that the Ridge terminates even closer to the coast where it seems to be cut off by a NE-SW trending fault. This interpretation is not possible to verify in any detail due to very few seismic lines here and the very shallow water depth, which leads to a very poor resolution and penetration in the seismic lines. The structures just mentioned are suggested by dashed lines in Fig. 6-1.

The vertical offset of the Linderödsåsen Ridge is estimated to be around 200 metres onshore. The Ridge is not considered by us to have any major extension into the Hanö Bay. Fault B (Fig. 6-1), acts as the northeastern uplifted fault scarp of a southwesterly tilted block associated with the Linderödsåsen Ridge, however. This latter Ridge is traversed by the two faults H and I mentioned above (Fig. 6-1), and the Ridge terminates against fault I. The faultline C (Fig. 6-1) forms a very complex, reactivated, sedimentary fault in the extension of the Ridge fault scarp B. Further southeastwards in the Bornholm Gat the sedimentary fault C is displaced towards SW by sinistral movements along faults E and F (D in Fig. 6-1). This complicated tectonic setting is demonstrated in the seismic profile Fig. 6-2, in which the wide complicated

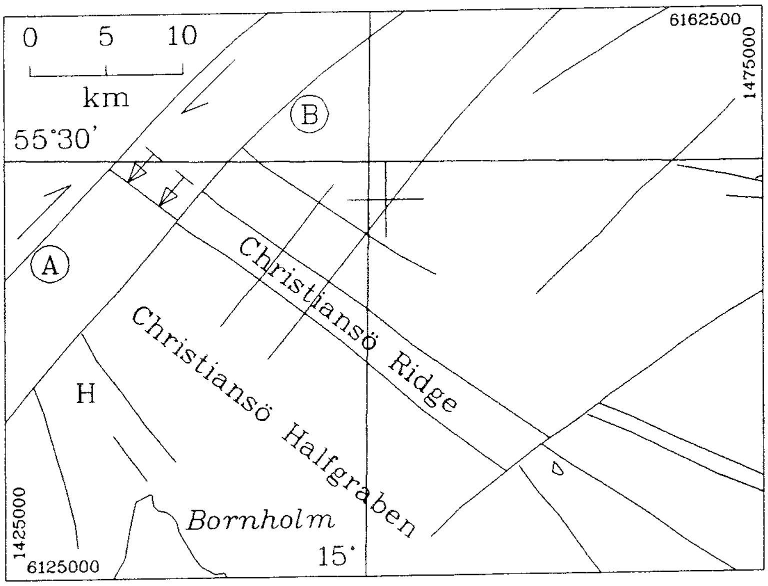

Fig. 6-3 Tectonic pattern of the Christiansö Ridge. H - Hammervand High, faults A and B are described in the text. Location of map is shown in Fig. 1-1.

fault-zone north of the Långagrund Ridge is marked (b in Fig. 6-2).

6.2.3 The Kullen-Christiansö Ridge System. The Christiansö Ridge is interpreted to form the offshore continuation of the NW-SE trending Kullen-Ringsjön-Andrarum dislocation zone (Norling & Bergström 1987). This Late Paleozoic fault zone, which became reactivated in the Triassic, may well be one of the most important tectonic elements in the development of the Hanö Bay Halfgraben. The Scanian part of the dislocation zone is here interpreted to continue in the Långagrund Horst (Wannäs 1979), which in accordance with the terminology used in this paper is now called the Långagrund Ridge.

The Långagrund Ridge is formed of a basement block covered with Paleozoic strata. It is delimited to the northeast by a major normal vertical fault (A in Fig. 6-1). Towards the southeast, the Ridge is terminated by a NE-SW trending fault system close to the Scania coast (F in Fig. 6-1).

The continuation of the Kullen-Christiansö Ridge System across the Bornholm Gat forms a strongly block-faulted segment. This segment is traversed by at least four subparallell NE-SW faults, which have been affected by dextral and sinistral movements as well as different vertical displacements. The irregularity in the morphology of the basement blocks is mainly a result of Mesozoic and Tertiary lateral movements along reactivated faults during several tectonic phases. The tectonic outline of the segment between the Långagrund and Christiansö Ridges is not fully evaluated here, as its very complicated development, is closely related to the evolution of the Bornholm Gat itself. These problems are only briefly described on pp. 13-15.

The Christiansö Ridge, which north of Bornholm is a very distinct morphological feature in the seabed, terminates towards the Bornholm Gat in the NW against a NE-SW trending fault, (B in Fig. 6-3).

NE-SW strike-slip movements in the Bornholm Gat part of the Kullen-Christiansö Ridge System are indicated by the displacement of a downfaulted ridge segment between the faults A and B (Fig. 6-3). This displaced segment was outlined already by Kumpas (1982) in his map of the basement surface. The segment is indicated to have been displaced some 2.5 km towards the southwest as indicated by the two arrows in Fig. 6-3.

The area between the Christiansö Ridge and Bornholm, including its northwestern offshore prolongation in the Hammervand High (H in Fig. 6-3), is named the Christiansö Halfgraben (Vejbaek

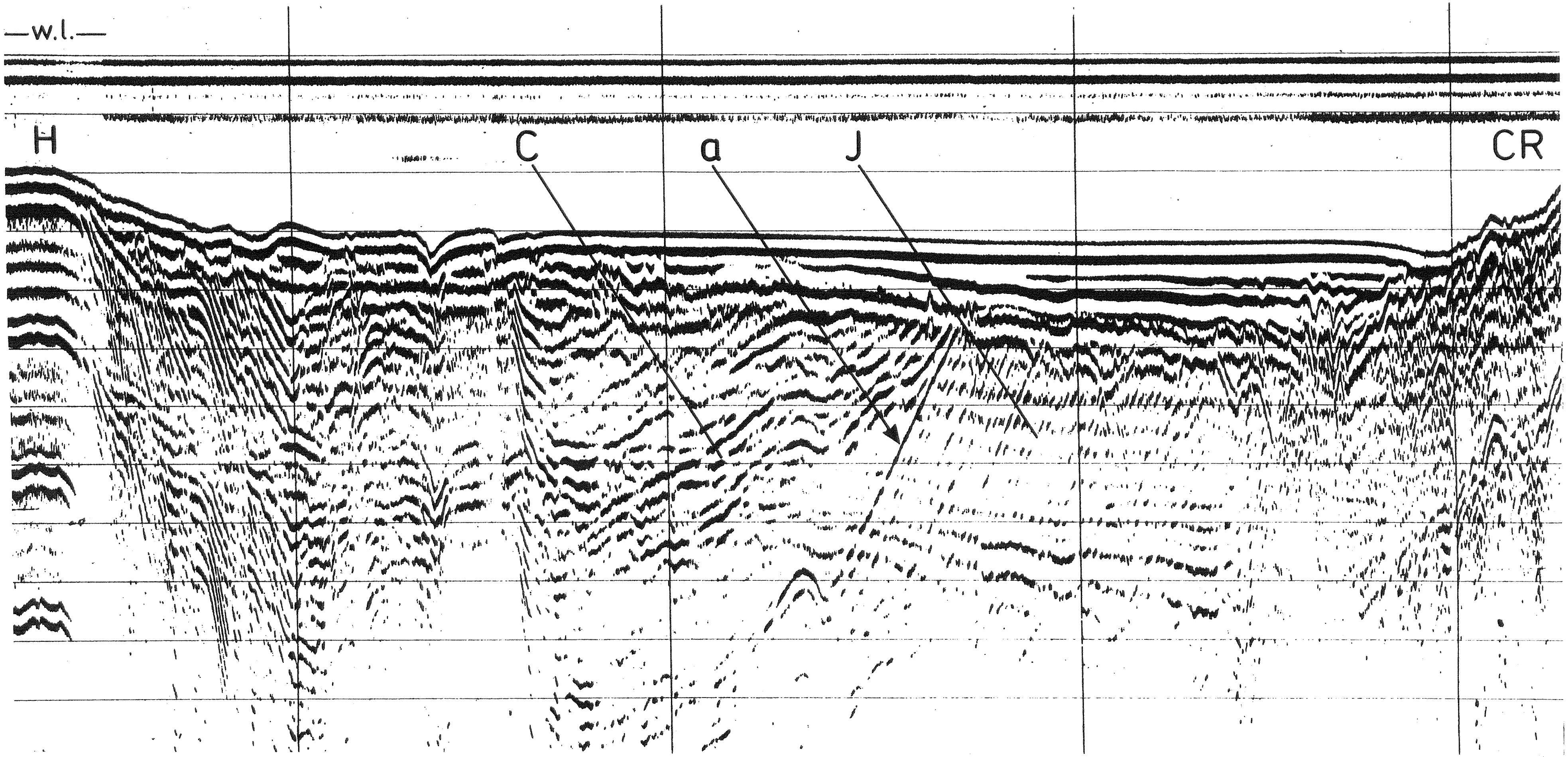

Fig. 6-4 Seismic profile across the Christiansö Halfgraben from Hammervand High (H in Fig. 6-3) in the southwest to the Christiansö Ridge (CR) in the northeast. J - Jurassic tilted strata, C - Cretaceous strata. The Jurassic and the Cretaceous sequences are separated by an angular unconformity (a). The location of the profile is marked 2 in Fig. 5-2.

1985). From the Christiansö Ridge towards Bornholm the strata become successively younger. The sequence is tilted towards the SSW and eroded. An angular unconformity (a in Fig. 6-4) is tentatively interpreted as the boundary between the Jurassic and Cretaceous. This unconformity is clearly seen in the seismic profiles. The unconformity has a general NW-SE strike in the Christiansö Halfgraben, it disappears northwest of NE-SW trending fault B (Fig. 6-3). The abrupt disappearance of this unconformity indicates very young movements along the NE-SW fault and it seems appropriate to make a comparison with the Vomb Trough in Scania where the Jurassic sequence has been tilted to a near vertical position along the Fyledal Line (Bölau 1973). According to Norling & Bergström (1987), the sequence along the Fyledal Line was tilted during the Late Kimmerian phase and possibly during younger phases.

The interpretation of the Christiansö Ridge (Fig.

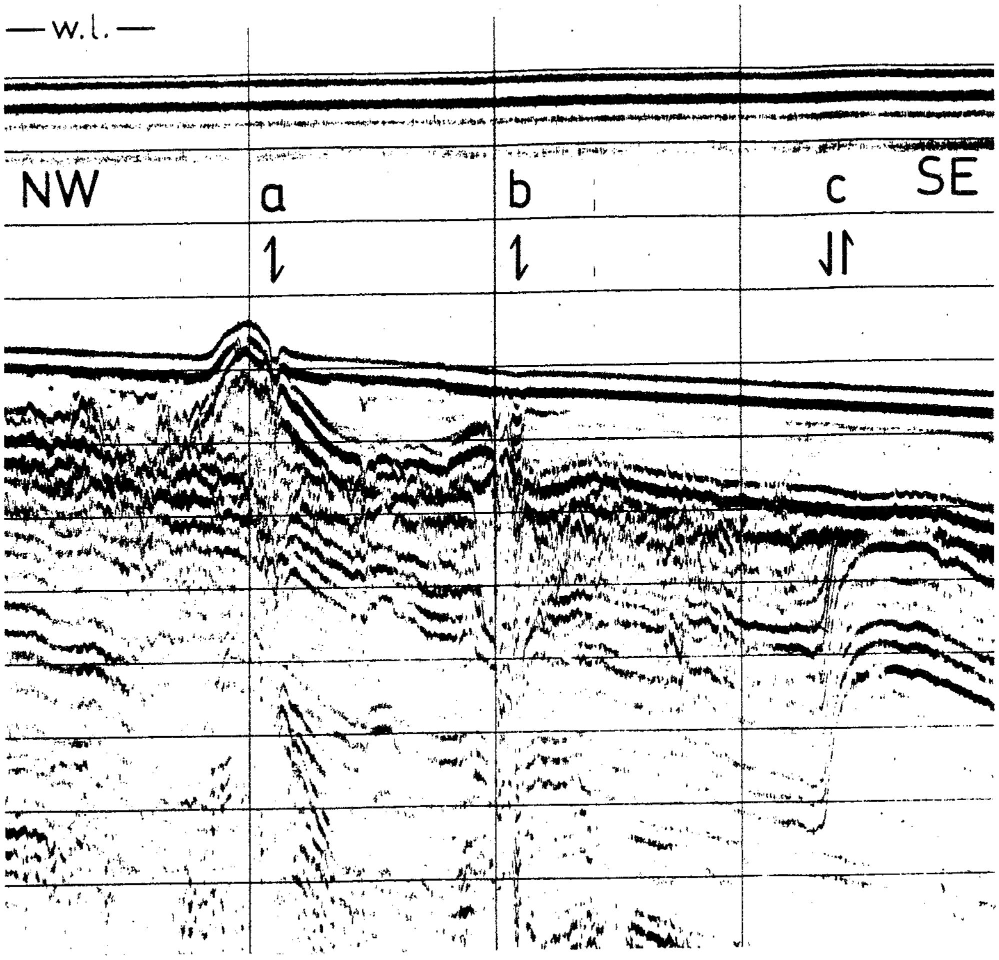

Fig. 6-5 Seismic profile across the Christiansö Fault (c). Neotectonic features are common in the Hanö Bay Halfgraben (a and b). The location of the profile is marked 4 in Fig. 5-2.

6-3) as a classic horst structure is only partly correct. The Ridge is a tilted basement block with a southwesterly dip, similarly to the basement blocks in Scania (Fig. 6-4). It is traversed by several NE-SW faults. The northeastern fault scarp of the Ridge has a vertical offset around 1000 m (Kumpas 1980). It is here classified as a synsedimentary fault, interpreted to be still

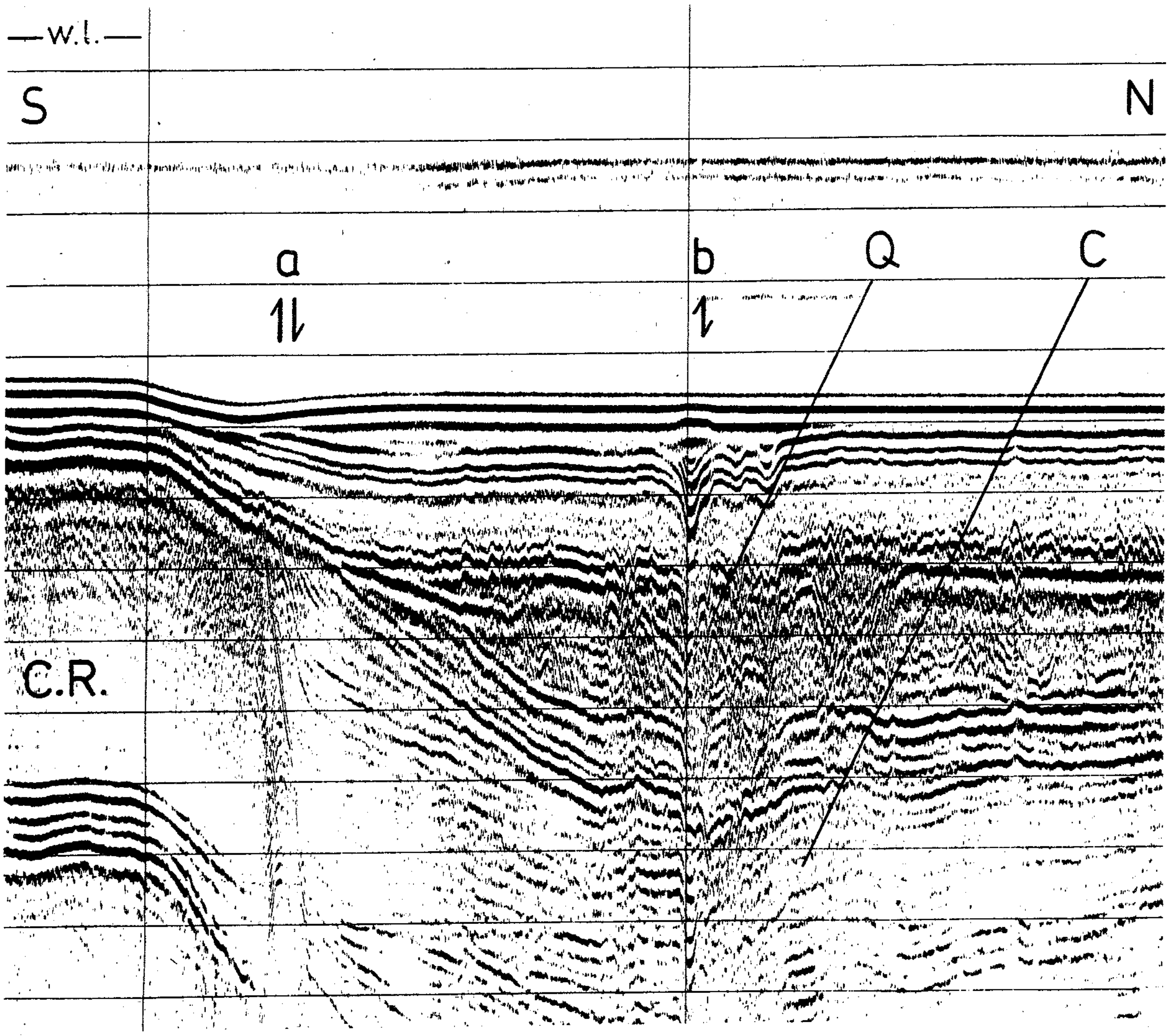

Fig. 6-6 Seismic profile across the southeastern part of the Christiansö Ridge (CR). a - northeastern fault scarp of the Christiansö Ridge, b - neotectonic fault parallelling the Christiansö Ridge (see Fig. 5-2). The differences in dip within the Cretaceous sequence (C) and at its upper surface, the anomalously thick Quaternary sequence (Q), and the structural indicators in the Late Glacial and Postglacial sequences are all indicators of prolonged and still active sinking of the Hanö Bay Halfgraben. Horizontal and vertical scales are described on p. 5. The location of the profile is marked 3 in Fig. 5-2.

active (Fig. 6-6 and p. 37). The outline of the Christiansö Ridge as a horst block in tectonic maps is mainly due to the fact that its southwestern limit most probably has acted as a hinge fault with a small vertical offset lending the block a general dip towards Bornholm.

Southeast of the Christiansö Island the northeast limit of the Christiansö Ridge is well defined, whereas its southwestern limit is rather uncertain. This is because of very few seismic lines in the latter area. The block is most probably traversed by several faults in the SW-NE direction and possibly also by subparallel faults in the general NW-SE direction.

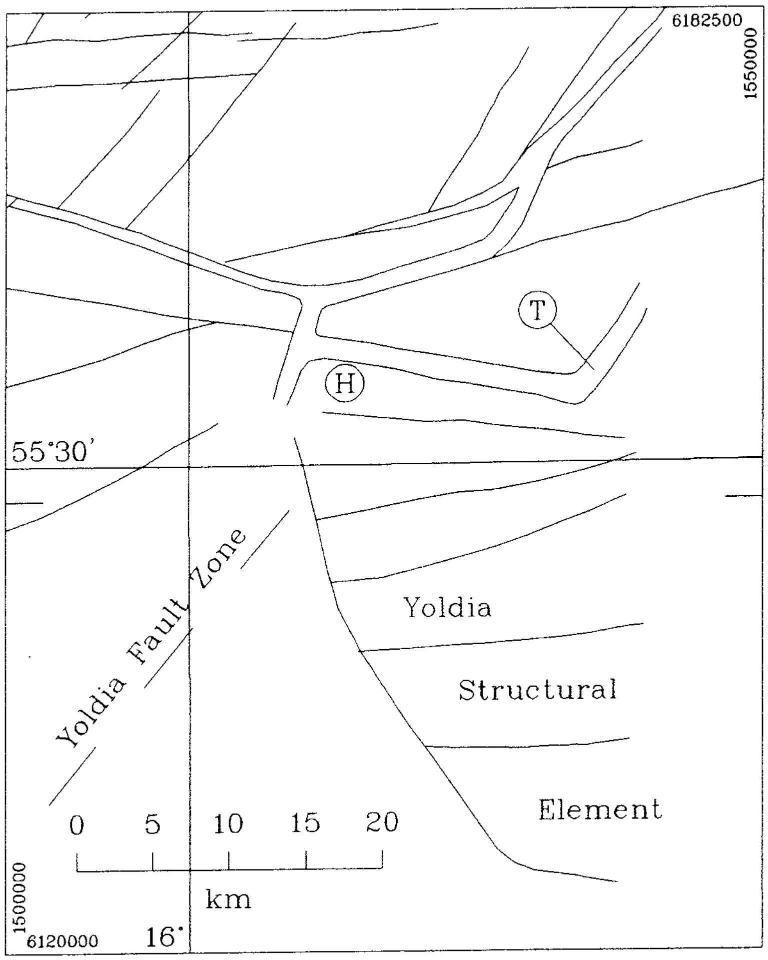

Fig. 6-7 Tectonic pattern of the Yoldia Structural Element. The Yoldia Structural Element is dominated by faults of varying trends from WNW-ESE to WSW-ENE. The Structural Element is boundered to the north by a WNW-ESE hinge line (H) of an approximately Variscan trend which furthermore conforms with a Glacially eroded trench (T). Trenches of this kind are common along the lineaments of this area (Fig. 5-2). For location of the map, see Fig. 1-1.

The Christiansö Fault (Fig. 6-5) is one of the faults which traverse the Christiansö Ridge in the NE-SW direction (Figs. 5-1 and 6-3). The northwestern side is downfaulted as a normal sedimentary fault (c in Fig. 6-5). In the northeast direction the fault is linked to a WSW-ENE fault, which partly borders the Yoldia Tectonic Element to the north (Fig. 5-2).

The border between the Hanö Bay Halfgraben and the Paleozoic basin in the east is tentatively outlined along a major sinistral strike-slip fault zone of the NE-SW direction, here named the Yoldia Fault

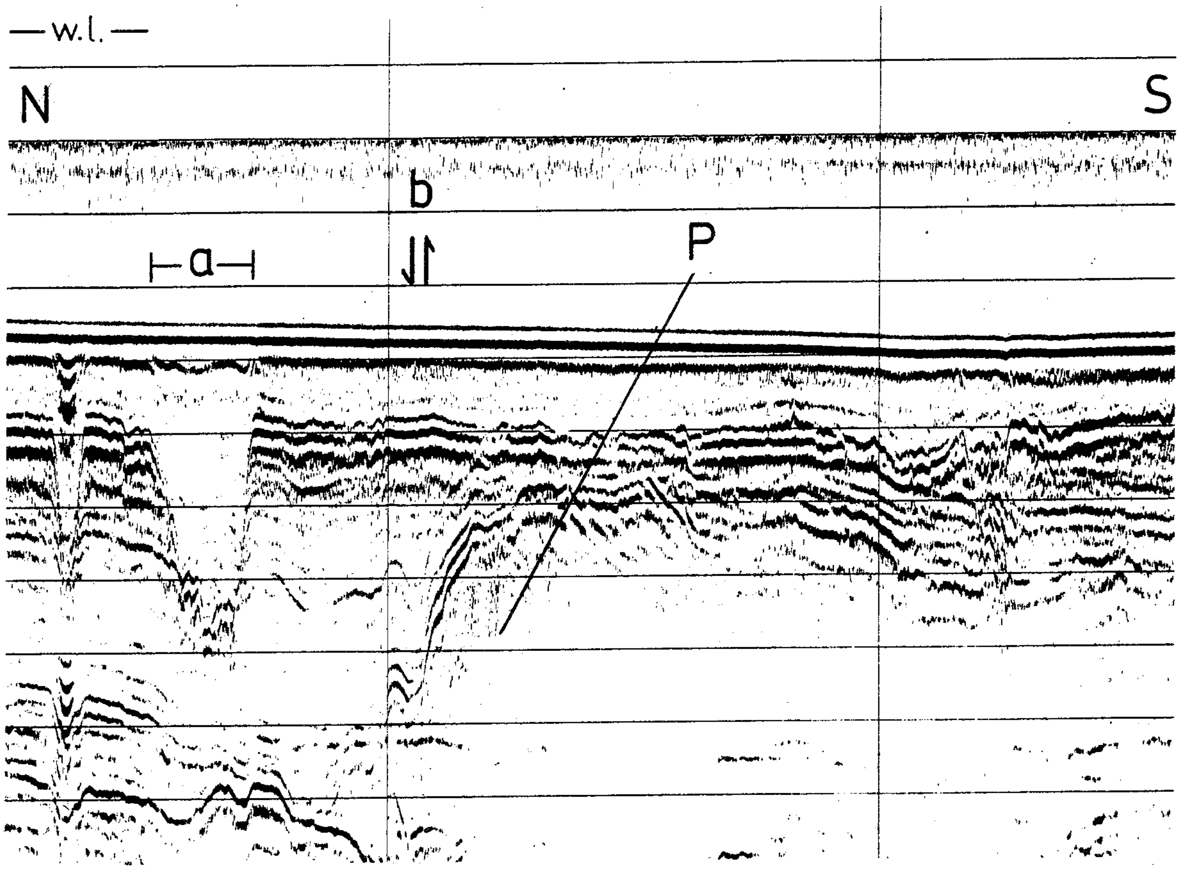

Fig. 6-8 Seismic profile near the intersection between the Yoldia Fault Zone and the erosional trench system at the northwestern boundary of the Yoldia Structural Element (Fig. 6-7). The uplifted and tilted Paleozoic strata (P) are part of the Yoldia Structural Element which is bounded to the north by a WNW-ESE hinge line (b). The tectonic pattern has controlled the outline of Glacially eroded trenches, some of which are presently active as neotectonic faults (a). Horizontal and vertical scales are described on p. 5. The location of the profile is marked 7 in Fig. 5-2.

Zone (Fig. 5-1). The Yoldia Fault Zone continues in the NE direction towards the Central Baltic Proper. The Fault Zone is linked to the WNW-ESE hinge line of the Yoldia Structural Element (H in Fig. 6-7) but it seems also to have acted as one of the hinge lines which separate the Kalmarsund Slope from the Baltic Syneclise. The Fault Zone continues northeastwards in the general direction of Gotland. The Christiansö Ridge may be dextrally offset by as much as 8 km at its junction with the Yoldia Fault Zone (Figs. 5-1, 5-2). However, a probably more adequate explanation involving a sinistral offset of a lesser magnitude, is that lateral movements activated and inverted fault blocks subparallel to the general NW-SE striking Christiansö Ridge. This explanation points towards a sinitral offset of only 2-3 km (Fig. 6-6).

The pre-Cretaceous development of the Yoldia Fault Zone between the Christiansö Ridge and the northern limit of the Yoldia Structural Element is not accessible to investigation in the present seismic material because of thick Cretaceous overburden.

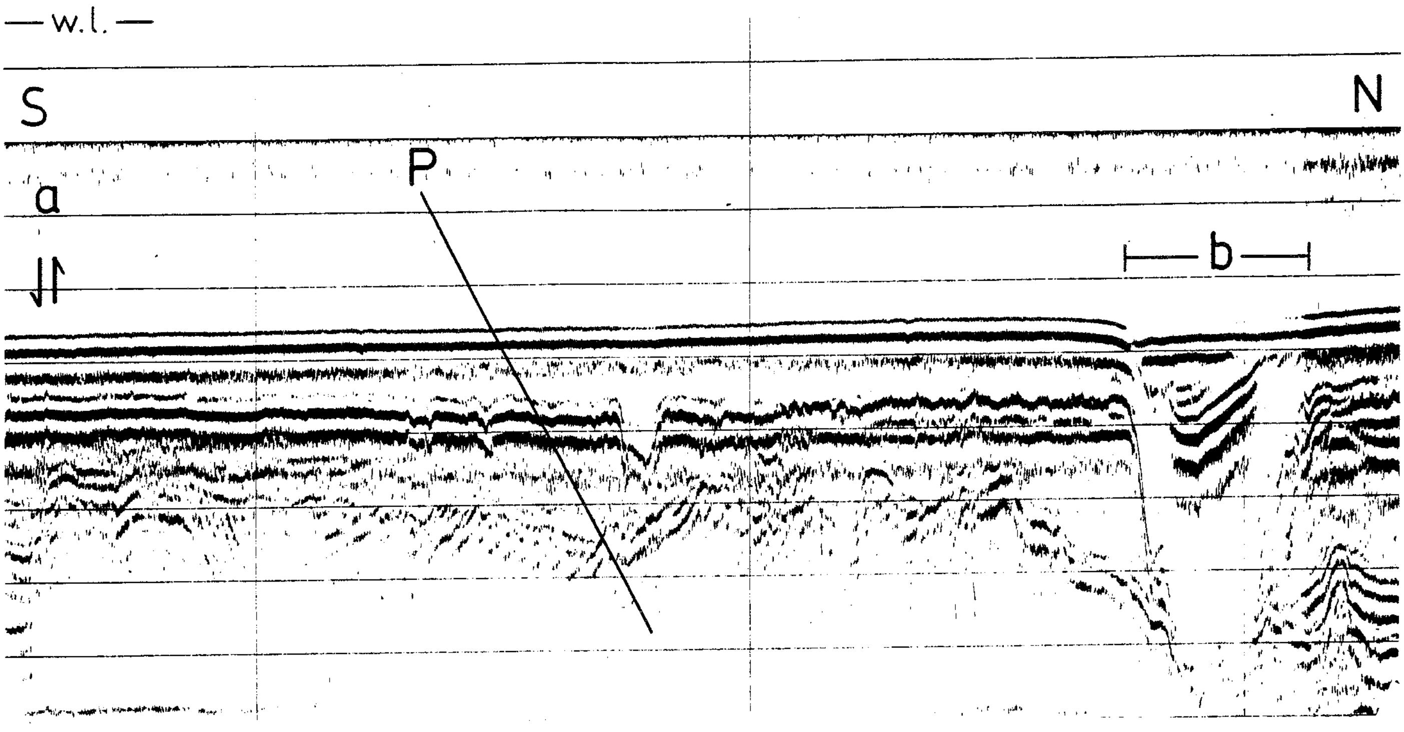

Fig. 6-9 Seismic profile across the Yoldia Structural Element showing tilted and fractured Paleozoic sediments (P). A fault in the Structural Element is marked (a). A glacial trench (b) has been eroded along the Yoldia Hinge Line (H in Fig. 6-7) which delimits the Structural Element to the north. Horizontal and vertical scales are described on p. 5. Location of the profile is marked 8 in Fig. 5-2.

The location of the Zone in this section is suggested by dashed lines in the present maps (e.g. Fig. 5-2).

The strike-slip fault along the Yoldia Fault Zone and associated left-lateral movements of the last detectable segment of the Kullen-Christiansö Ridge, is regarded by us to be of major importance for the tectonic development of the Yoldia Structural Element.

6.3 THE YOLDIA STRUCTURAL ELEMENT

The Yoldia Structural Element located in the easternmost part of the investigated area, is named after a boring in the area, performed by Svenska Petroleum Exploration AB in 1987. The Structural Element is limited to the north by a WNW-ESE trending hinge line (H in Fig. 6-7, b in Fig. 6-9). The tectonic style of the Yoldia Structural Element shows a strong tectonic influence after that the Submesozoic peneplain was developed in the Hanö Bay. The Paleozoic stratal sequence (P in Fig. 6-9) is uplifted, tilted and faulted, quite opposite to the conditions within the surrounding very smooth Submesozoic peneplain area. It is traversed by faults of the WNW/WSW to ESE/ENE directions (see Fig. 6-7). The cover of Mesozoic sedimentary rocks is rather thin, about 100 m, over the tectonic element compared to several hundred metres in the areas west and south of the Element.

The trench system north of the Yoldia Structural Element was probably formed along Variscan tectonic faults which we interpret as rejuvenated during the Laramide phase in the Late Cretaceous to Tertiary. These rejuvenated faults were later subjected to Glacial erosion and neotectonic movements, which led to the present system of infilled trenches. Vertical offsets within the trenches (b in Fig. 6-9), indicate neotectonic movements.

6.4 THE KALMARSUND SLOPE

The Kalmarsund slope has a southeasterly dip, contrary to the SSW dip of the Hanö Bay. Paleozoic sedimentary rocks dominate this area, represented by Cambrian-Silurian strata, which increase in thickness towards east and southeast. The tectonic pattern of the slope is only outlined in its southern part, where the NNE-SSW direction dominates together with an approximately E-W direction.

7 DISCUSSION

The objective of this paper is to present a structural outline and timing for the development of the Hanö Bay and its relation to the Tornquist Zone. Naturally the ideas advanced in this paper require further qualitative and quantitative evaluation on a local and regional scale. To some extent, they should therefore be regarded as working-hypothesis. Below is the development described following the proposed scheme in fig. 7-1.

The Hanö Bay has been subdivided into four areas of different geological settings; the Kalmarsund Slope, the Hanö Bay Slope, the Hanö Bay Halfgraben and the Yoldia Structural Element. The latter element is located to the eastern edge of the Hanö Bay Halfgraben. The Bornholm Gat, located in the central part of the Tornquist Zone, is strongly reactivated by several orogenies. The tectonic development of the Bornholm Gat is therefore closely related to the development of the Hanö Bay.

The Tornquist Zone separates the East European Platform to the northeast from the Central European Platforms in the southwest, it extends across Scania as a raised and strongly faulted NW-SE trending zone. Some of the basins along the Tornquist Zone seem to be associated with crustal failure in an extensional tectonic regime.

The map presented in Fig. 5-2 results from a different approach compared to previous tectonic presentations of the Tornquist Zone. Thus, the tectonic outline in this map is based on single-channel seismic profiles and not on multi-channel recordings. The high resolution in these profiles has the result that even comparably small vertical offsets, as in neotectonic faults, can be detected. Thus, the different tectonic systems appear to be more closely linked to each other than known before.

The NE-SW and NW-SE directions in the Hanö Bay are inherited Precambrian directions, which have been recurrently rejuvenated during most of the Fanerozoic tectonic phases.

The WNW-ESE direction was probably initiated during the Variscian/Hercynian Orogeny. In part it acts as hinge-faults for the Hanö Bay Halfgraben. This fault direction seems also in part to be linked to the faults related to the Bornholm Gat Tectonic Zone.

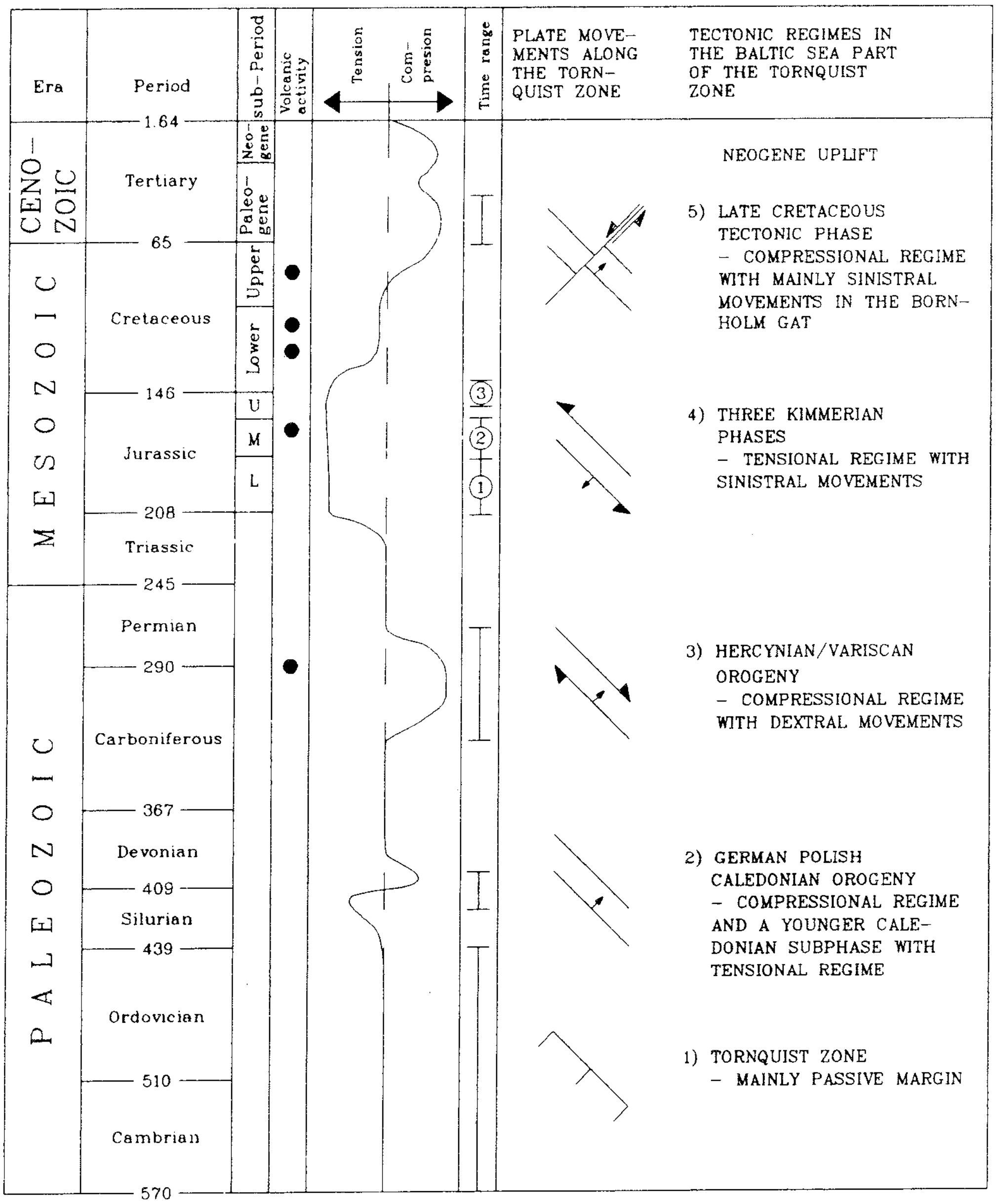

Fig. 7-1 The values related to the tension/compression graph do not show any accurate relations to the past. A proposed explanation of tectonic development of the Baltic Sea part of the Tornquist Zone.

The Bornholm Gat is dominated by two intersecting tectonic directions; the NW-SE direction representing the Tornquist Zone and the NE-SW direction representing a reactivated Precambrian direction, which during the Late Cretaceous to Tertiary Laramide phase initiated the inversion tectonics in the Gat. Sinistral strike-slip movements in the order of 2-3 km are interpreted to have occurred along NE-SW trending faults in the Bornholm Gat. This phase has also affected the development of the Hanö Bay area.

This interpretation is based on the fact that most of the NE-SW faults in the Hanö Bay have their downfaulted sides towards northwest, which is consistent with the Late Cretaceous transpressional movements rather than with the Tertiary uplift of Scania. Furthermore, the major discordance which marks the approximate location of the Cretaceous-Jurassic boundary north of Bornholm is offset by lateral movements along the NE-SW system at the boundary to the Bornholm Gat, and this boundary is nowhere to be found in the Gat. This points towards at least a Late Cretaceous age for the lateral movements in the Gat.

On the other hand we find no convincing evidence on major dextral movements in the Bornholm Gat in the Late Cretaceous. The Late Cretaceous tectonic development seems to be mainly transpressional and sinistral. The NW-SE system associated with the Tornquist Zone is truncated by the NE-SW fault system in the Gat.

The NW-SE system in the Hanö Bay is primarily associated with the Kullen-Christiansö Ridge System and affects the southern parts of the Hanö Bay Halfgraben. Thus, synsedimentary faults are proposed to have taken place in the southern parts of the Hanö Bay Halfgraben, along the Kullen-Christiansö Ridge System, during the main subsidence phases. No direct prolongations of the Nävlinge and Linderöd Ridges into Hanö Bay have been found during the present investigation. On the contrary, the faults associated to the two Ridges seem to terminate closely offshore towards a set of NE-SW oriented scissor faults. The Nävlinge Flexure, discussed by Kumpas (1980), is not interpreted as any major structural feature in the Hanö Bay.

The development of the Hanö Bay is here subdivided in five phases, namely:

1. Early Paleozoic. The Tornquist Sea, which developed as an easterly branch of the Iapetus Ocean, separated the Baltic Shield from a microplate associated with the Gondvana Continent (Nuegebaur 1989) during the transition to the Paleozoic.

During the Cambrian, a period of tectonically stable conditions prevailed, and the Tornquist Zone seems to have formed a passive margin.

In general, the Paleozoic sediments - mainly the Ordovician and the Silurian - show rapidly increasing thicknesses to the east and the south along the Baltic Sea part of the Tornquist Zone. By discussing the crust along the Tornquist Zone in the terms of independently moving tectonic blocks, it may be possible to explain the differential subsidence and the changing sedimentary pattern between the local sedimentary basins.

Remnants of Paleozoic sedimentary rocks in adjacent areas indicate clearly that the Hanö Bay was part of the Cambro-Silurian depositional area, although the sequences were almost totally removed during the Late Paleozoic erosional period.

2. Middle Paleozoic. The tectonic deformation resulting from the closing of the Iapetus Ocean between Laurentia and Baltica, seems to have resulted in an extensional tectonic pulse along the Tornquist Zone. Thus, the Tornquist Zone acted as a passive margin during Cambrian and the main part of Ordovician. In the Silurian, the main NW-SE direction of the Tornquist Zone was reactivated which resulted in syn-depositional structural elements in Kattegat and in the formation of the Colonus Shale Trough in Scania. The Colunus Shale Through was mainly developed during Ludlow (Late Silurian) and this tectonic reactivation is here called the Caledonian Subphase.

In the northeastern part of the Hanö Bay, the Kalmarsund Slope is separated from the Baltic Syneclise in the east by a NNE trending hinge zone east of Öland. The effects of the closure of the Iapetus Ocean may be indicated by hinge effects along NNE trending fault zones in the Baltic Syneclise. This Caledonian Subphase changed the structural development in the southeastern parts of the Baltic Sea, the timing of this event is somewhat later then in Scania, i.e. Pridoli in the uppermost Silurian. Thus, tectonically the Baltic Syneclise was mainly developed during the Paleozoic which is quite opposite to the conditions in the Hanö Bay. The Tornquist Sea gradually was closed due to the compression from Central Europe which formed the so called German-Polish Caledonian orogeny along the Tornquist Zone.

The change to a compressional regime, resulting in the Caledonian Deformation Front along the Tornquist Zone, seems to have been rather weak (Neugebauer 1989), as the German-Polish Caledonides were developed. The general uplift that affected the East European Platform as well as the Central European Plates during the Devonian led to the development of the so called Old Red Continent.

A number of questions, which relate to how the Tornquist Zone was affected by the Caledonian Orogeny and by the transition to the Hercynian/Variscan Orogeny, remain unsolved.

<u>3. Late Paleozoic</u>. The Hercynian/Variscan orogeny resulted in a general upwarping along the southwestern part of the East European Platform. In the Late Carboniferous-Early Permian, magmatic and tectonic activities along the Tornquist Zone initiated the development of the Oslo Graben. This tectonic regime further caused a rejuvenation of the Ringköping-Fyn High, accompanied by subsidence of surrounding basins.

The dominating compressional regime in Central Europe is here tentatively interpreted to result in secondary WNW-ESE transtensional movements in Scania. This may explain the extensive dolerite volcanism in Scania, disregarding the concept of a general NE-SW extension.

<u>4. Early Mesozoic</u>. The Triassic started with a change in the tectonic regime from transpressional to transtensional, resulting in a subsidence phase in the Central European Basin. The Hanö Bay Halfgraben, which is separated from the Hanö Bay Slope by the southeasterly trending Hanö Bay Flexure, was probably initiated in the Late Triassic, although its main subsidence phase occurred during the Late Cretaceous. The Halfgraben is infilled by a Mesozoic to Quaternary sequence on top of local remnants of possible Lower Paleozoic.

The Kullen-Christiansö Ridge System delimits the Hanö Bay Halfgraben towards the south. It is a 250 km long structural feature, which furthermore has a northwestward prolongation into the Kattegatt and the Danish Basin. The prolongation towards Poland is unfortunately unknown at present. This Ridge System is considered to be the most important structural feature for the development of the Hanö Bay Halfgraben.

The three Kimmerian tectonic phases from Late Triassic to Early Cretaceous affected the Tornquist Zone into a complex array of blocks which were uplifted and eroded. Several basins, related to the uplifted blocks, were during the same time subjected to subsidence. The Upper Triassic to Lower Cretaceous sequence onshore Bornholm show a series of hiata, which indicate a strong tectonic control of the basin evolution (Gravsen et al 1982). The transtensional regime, which dominated during the Kimmerian tectonic phases, was caused by sinestral movement along the zone.

The first of the three Kimmerian phases is here interpreted to reactivate the Kullen-Christinasö Ridge and to initiate the Hanö Bay Halfgraben. The last Kimmerian phase resulted in the main subsidence phase of the Halfgraben, whereas the

Middle phase seems not to have affected the Hanö Bay to any major extent.

5. Late Mesozoic. The tectonic regime changed gradually in the Late Cretaceous as large parts of the Tornquist Zone underwent an active subsidence. The timing and separation of the Late Cretaceous phase from the younger Tertiary (Laramide) phases in the Bornholm Gat and the Hanö Bay are very complicated, as we have no exact chronostratigraphic controll on the seismic markers in the uppermost part of the Cretaceous and possibly Tertiary strata in the Hanö Bay. Therefore, these tectonic phases are not subdivided in the present scheme of the tectonic development of the Tornquist Zone.

The Alpine orogeny, resulted in a new transpressional field with uplifted inversion structures along the major part of the Zone. The Late Cretaceous (Santonian-Maastrichtian) phase involved a major inversion phase and a reactivation and rapid subsidence of the Hanö Bay Halfgraben.

The NE-SW fault direction seems to have been reactivated as strike-slip faults, at least during the Alpine orogeny (Laramide phase). Several subparallel faults with same direction can be found east of Bornholm, where the similar type of inversion structures are common. The strike-slip movements with related inversion tectonics in the Bornholm Gat have had a major influence on the present tectonic outline of the Gat. The structural style of the inverted basins is very variable and seems to be related to the pre-Mesozoic structural configuration.

The tectonic style of the Yoldia Structural Element indicates a strong tectonic influence after that the Submesozoic peneplain was developed in the Hanö Bay. The Paleozoic stratal sequence is uplifted, tilted and faulted, quite opposite to the conditions within the surrounding very smooth sub-Mesozoic peneplain area. The uplift of the Yoldia Structural Element is here interpreted to be a result of the Late Cretaceous tectonic phase.

Tectonic influence from the transpressional Laramide phase is furthermore interpreted to have affected the Hanö Bay Halfgraben, resulting in the sedimentary faults present in the western part of the Bay.

Post-Mesozoic. The final tectonic development of the Hanö Bay Halfgraben occurred in post-Maastrichtian (Kumpas 1980). The reactivation of the sedimentary faults in the Hanö Bay could be a result of the Tertiary uplift of Scania.

The Hanö Bay Halfgraben is proposed to undergo active subsidence along the Christiansö Ridge, which also explains the neotectonic faults in the Halfgraben. The ongoing subsidence of the Halfgraben is estimated to be in the order of 20-60 m during the Quaternary.

Two areas are of special interest in this respect, namely the area closely north of Christiansö island along the Kullen-Christiansö Ridge and the Yoldia Structural Element somewhat further to the east. In both areas neotectonic faults extend through the thickness of the Quaternary sediments, and pre-Weichselian erosional surfaces are vertically offset along fault lines. Closely north of Christiansö island, truncated Late Cretaceous sediments dip away from the Christiansö Ridge in a stepwise manner, which may have resulted from Quaternary movements, too.

It is a delicate matter to decide whether the vertical offsets in late- to postglacial sediment layering, recorded across pre-Weichselian Quaternary trenches in the eastern part of the Hanö Bay, are effects of sediment compaction or the result of neotectonic movements. In the seismic profiles (e.g. Fig. 6-9), the trenches show differential sinking along their two sides and, thus, the sediment structures cannot be explained by compaction alone. Therefore, it seems probable that movements currently occur not only along the Christiansö Ridge and within the Yoldia Tectonic Element, but also along many of the other tectonic faults in the Hanö Bay.

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