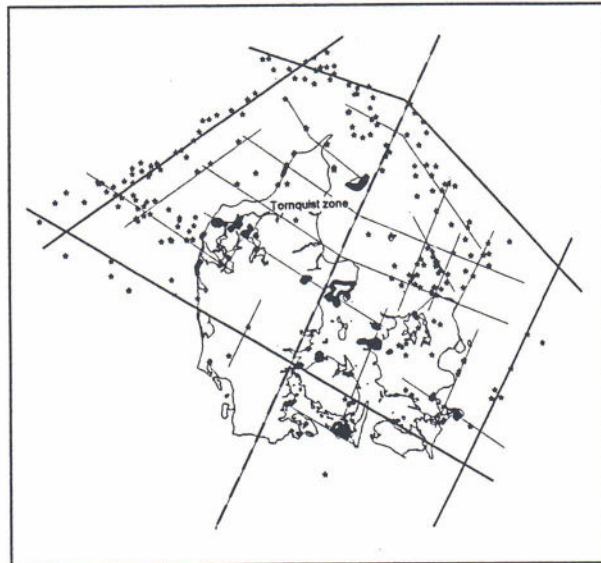


Premiliary study

*Development of the tectonic regime
in the broader area of the Danish basin
since Tertiary time*



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Introduction

This report forms a preliminary study of a larger project, which will take place during the academic year 1995 - 1996 for the University of Århus. The aim of the project will be the construction of a geological model of the broader area of the Danish Basin, in order to determine the potential stress field and the active existing deformation.

This preliminary study uses only existing published information, most of which comes from GeoKat project, which is an integrated marine geological research, of the Late Quaternary evolution of the Kattegat offshore area. Seismic sections, deep borehole data, pre - Quaternary surface maps and other published material obtained from this project were especially useful to complete this report. The official geological maps published by D.G.U. have been used as a basis. The rest of the information is collated from other older publications and maps, which have been judged useful for the aim of the project.

Some of this information have been digitized and imported in a G.I.S. (Geographical Information System) program called MapInfo. A G.I.S. program can combine different kinds of information and display them in a spatial position, by doing so, producing maps, in order to understand and explain our model.

There is a strong tradition in Denmark to relate all the deformed structures and disturbed beds to glacial processes. Lately however different signs of neotectonic activities have been reported and since then, more and more Danish geologists start to believe in tectonic deformation as a factor modifying the present landforms.

This preliminary study, just by using geometrical features, give an explanation about the potential tectonic development of the area from the Lower - Middle Tertiary until recent time. It also proves that the ice followed directions, were not randomly determined, but set by the tectonic pattern. Consequently some of the deformed surface structures have more tectonic than glacial origin. Finally this project aims to prove the existance of neotectonic action and to identify the stress field that creates it.

Tertiary

During Lower and Middle Tertiary Danish basin including Tornquist zone and Kattegat area was covered by sea. Biochemical deposition which has started in late Cretaceous, ends in Danien, where we have the Top Chalk formation. Younger of Danien, Tertiary formations, consist of various fluvial and marine deposits characterizing changes in the depth of the basin and the source of the material.

During this time we have the activation of a stress field in the area. This stress field is characterised by a major inverse pressure in a SSW - NNE direction, creating a sequence of synclines and anticlines (horsts and grabens) in a ESE - WNW direction inside the basin, as can be seen from the Structural map of Top Chalk Group (DGU 1991). These folding axes have at the same time a general plunge through WNW. This means that the major inverse pressure stress field of the area, is accompanied at the same time by a tilting around the SSW - NNE axis plunged through WNW. This tilting effect produces, weak zones in the direction NNE - SSW, which is perpendicular to the synclines - anticlines (horst - grabens) axes (*figure 1*).

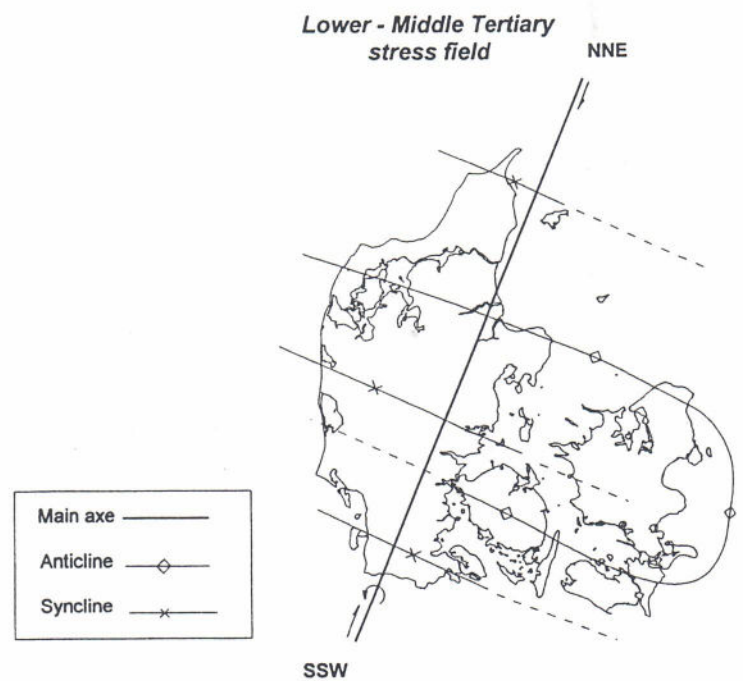


Figure 1

The same general direction (ESE - WNW) of anticlines - synclines (horsts - grabens), but expressed in a less dramatic way, can be seen in the Pre-Quaternary Formation map (DGU 1992). The existing younger sequences of Upper Miocene in the WSW area of the basin lead us to the conclusion that the same more or less stress field (a major SSW-NNE inverse pressure together with tilting around a NNE - SSW axis plunged through WNW) is active during almost the whole Tertiary.

In Upper Miocene - Middle Pleistocene we have a global change to the geological regime of the area. Due to a general uplifting, Danish basin became a land of net erosion. At the same time the stress field which was active during the Middle and Lower Tertiary, altered to a pure tilting around an ESE - WNW axis and plunged through SSW (*figure 2*). This tilting produced a smooth erosion in the SW part of the area which proportionally increased to much deeper one towards a northeastern direction. This mechanism explains the appearance of older sequences in the pre-Quaternary surface towards this direction (*figure 3*).

It is most probable that the new tilting affects the existing weak zones produced by the previous tectonic regime during the Lower - Middle Tertiary. The tectonic lines of ESE - WNW direction are still in action during this time but they function in a different way. This general new tilting separates the area in different parallel blocks of the same ESE - WNW direction. These blocks are following the major tilting, which plunged the area through SSW, but at the same time we have the creation of local stress fields due to movements between the blocks, producing small basins and inverse structures along these lines. As a result some of these areas of the pre-Quaternary floor, especially close to the active zone, possessed by a strong undulating relief (Holger Lykke-Andersen et al. 1993). One of these main block-zone is the tectonic Sorgenfrei - Torquist zone, the border between the Skagerrak - Kattegat platform and the Danish Basin.

During Lower - Middle Tertiary and possibly from an earlier time, this zone has been affected by the general stress field of the area. The main inverse SSW - NNE inverse pressure has formed a complex horst-anticlinorium, which is shown in a pre-Quaternary map (figure 4). Inside this zone we have older (Jurassic and Triassic, also some Precambrian or/and Paleozoic) formations and northeastwards and southwestwards we have younger (Upper Cretaceous - Danien) ones. The small relatively Lower - Middle Tertiary tilting can be seen due to the older Triassic formation appearance southeastwards, in relation to the Lower and Upper Cretaceous appear northwestwards of the block.

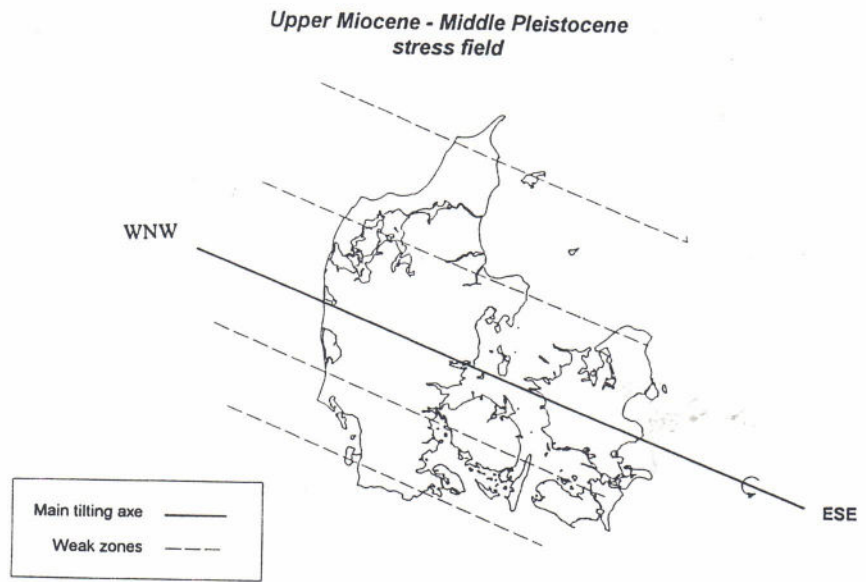


Figure 2

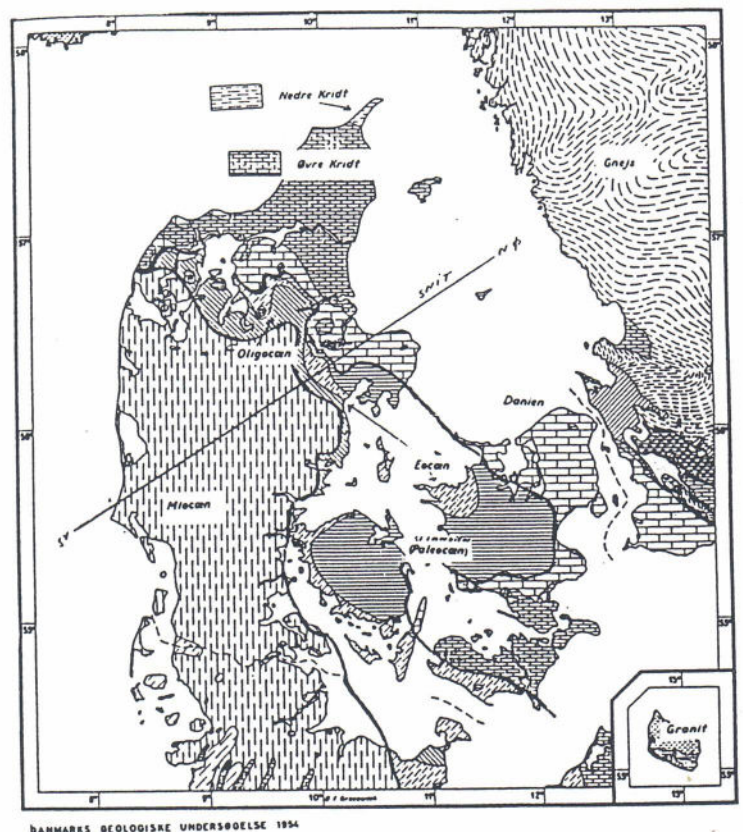


Figure 3 (ref. 6)

During the Upper Miocene - Middle Pleistocene where we have the global change of the geological regime the block continues behaving as a horst but at the same time, follows the general tilting of the basin through SE, as it can be observed from the old Precambrian formation which appears only in the northeastern part of the block (figure 4).

This structural complex horst-anticlinorium is followed by a morphological elevation as it is described from seismic data. Inside the Sorgenfrei - Torquist zone the general level rises gradually to less than 50 m b.s.l. (meters below sea level), where NW of this zone in the area of Upper Cretaceous formation the surface can be described as a peneplain at a level of 125 m b.s.l. (Kelvin G. Gyldenholm et al. 1993). This is an indication that the zone was still active during Pleistocene and that the tectonic forces were much stronger than the existing erosion. Quaternary displacements within this zone, indicate activity during recent time.

As we have already mentioned, this activity (tilting) during the Lower Pleistocene, was accompanied by smaller scale movements in the boundaries or within the blocks. Due to these movements, local stress fields have been produced creating basins or inverse structures (pull apart basin mechanisms). The appearance of such basins, in some cases with depths more than 250 m b.s.l, along the limits of the Sorgenfrei - Torquist zone are examples of this activity (figure 5).

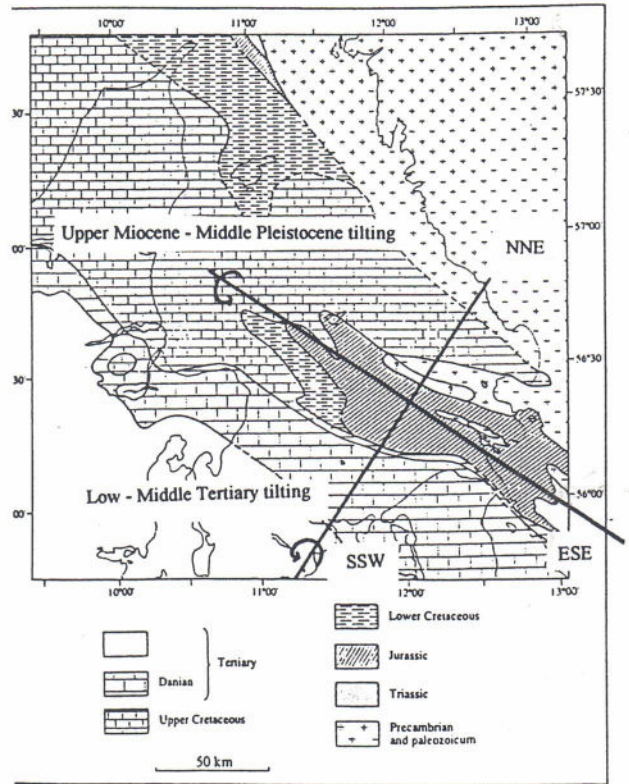


Figure 4 (ref. 8)

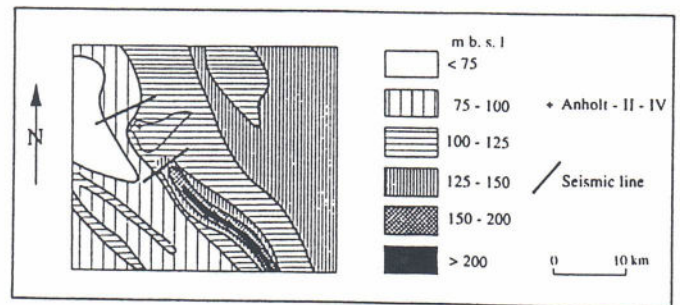


Figure 5 (ref. 9) p. 295

Quaternary

During Quaternary time two different dynamic processes affect the area. The first one is the tectonic regime which continues its activity through this period, the second is the ice action, which affects the area during the ice periods of glaciation. It is necessary to distinguish these two different dynamic processes which during some period of time were active simultaneously.

We have a lot of evidence proving that tectonic action was taking place in this area during Upper Miocene - Middle Pleistocene before the ice periods. Also we have a lot of evidence of neotectonic action after the ice periods during the Holocene. It is reasonable to believe, that tectonic action was also taking place during the ice periods.

To distinguish between these two different processes we have to take under consideration some of their characteristics.

- The deformation pattern produced by the ice affects the surface and is reducing as the depth is increasing. On the other hand structures of tectonic origin follows the opposite procedure. The deformation is increasing together with depth.
- Ice forces act for a short time period relate to the action of tectonic stress fields.
- During a short period of time, the ice action could be much more effective in relation to tectonic action, which is a much slower processes.

As a result of erosion during Upper Miocene - Middle Pleistocene and a certain amount of subsidence a new large basin in northern Denmark was formed. This subsidence has to be correlated with the sea level changes in order to determinate the net amount of the land movement.

The last stress field that affected the area during the Upper Miocene was a tilting around a ESE - WNW axe and plunging through WSW. This action creates the diverse erosion which is seen on the pre - Quaternary surface (*figure 3*). In this new depositional period which started approximately in Middle Pleistocene, we have thick sequences of deposits in the Northern part of Jutland, as it can be seen from the Pre - Quaternary surface topography map of Denmark (D.G.U. 1994). These relatively deep basin doesn't fit with the last tectonic regime, which was to tilt the area in the opposite direction. At the same time, an established tectonic stress field can't change so easily in a short period of time and the tectonic regime of the Holocene doesn't fit as well with this subduction. These facts lead us to the conclusion that this sudden subduction of the Northern part of Jutland has been created by the ice covers during that time.

This relatively quick subduction of the northern block - blocks is accompanied by, at the same time, the tectonic stress field, which is still in action but functions at a much lower speed. The tectonic weak lines however, which determinate the blocks, have a vital importance for the ice cover

movement. The subduction of northern Jutland, caused by the ice during that period, still uses the active tectonic limits of the Tornquist zone to subduct the area (figure 6).

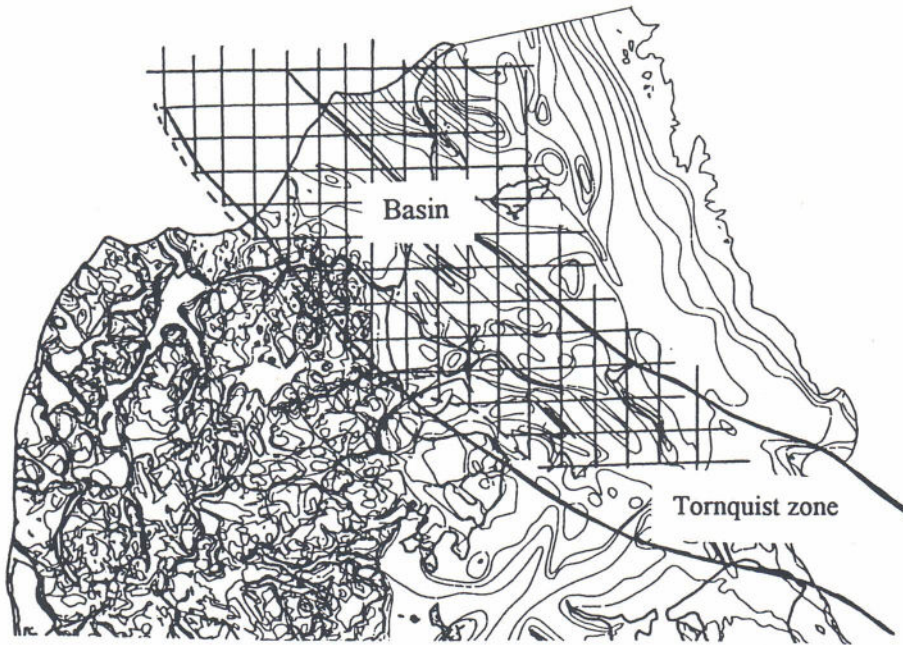


Figure 6 (ref. 11)

During ice periods, ice movements, follows set directions which are not randomly determined. The two main linear zones, created by tectonic action in the area, are the WNW - ESE lines, which determine the main direction of the blocks development and the NNE - SSW direction perpendicular to the first one, is created as a result of tilting of the blocks. It is not a coincidence, again, that the development of the fjords in the eastern part of Jutland follows the first WNW - ESE direction (Horsens, Vejle, Kolding fjords) and some of them coincide with active faults during the Tertiary. On the other hand, we have the development of fjords (Roskilde, Ise fjords) and the parallel development of Storebælt (channel between Fyn and Zealand) and Øresund (channel between Sweden and Sealand) in the second direction NNE - SSW perpendicular to the first one (figure 7).

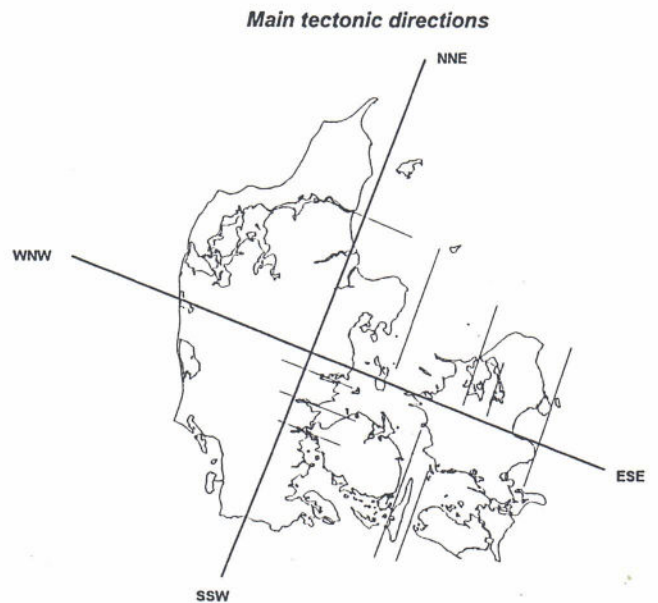


Figure 7

A very good correlation also exist between the lineament pattern of the surface and the subsurface structures (H. Lykke-Andersen 1981) (*figure 8*). The rose diagram of azimuthial distribution of the topografic lineaments in Denmark shows two main concentrations (*figure 9*). The first one WNW - ESE is the main direction of the block development and the second one NNE - SSW is the one (perpendicular to the first) which has been created by the tilting of the blocks. If we accept that the creation of the surface releif is caused by the ice, then it is reasonable to believe that the ice movement has been determinated entirely by the tectonic pattern.

During the Holocene, we have a major uplifting caused by an inverse pressure of the area in a SSW - NNE axe which has to be correlated again with the sea level changes. At the same time we have a tilting around that axe plunging the area through WNW. This new tectonic regime which has been started since the Upper Pleistocene or maby earlier, is like the tectonic regime that affected the area during the Lower - Middle Tertiary (*figure 10*).

The tilting is clearly shown by seismic section in the Kattegat area (Kelvin G. Gyldenholm et al. 1993), where we have dislocations and foldings especially in the area of Store Middelgrund and Rødebanke. As can be seen in the section (*figure 11*), the unit 3 which is classified as an older glacial/interglacial deposits by Sveriges Geologiska Undersokning (1989) has been divided into several smaller blocks, which follow the same tilting movement. The top of the unit is clearly erosional and the units 1 and 0 corresponding to Weichselian glaciomarine clays and the Holocene don't cover the unit 3 but they are

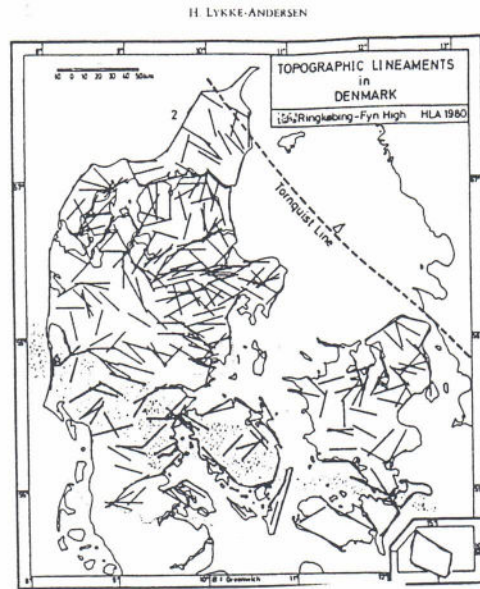


Figure 8 (ref.7)

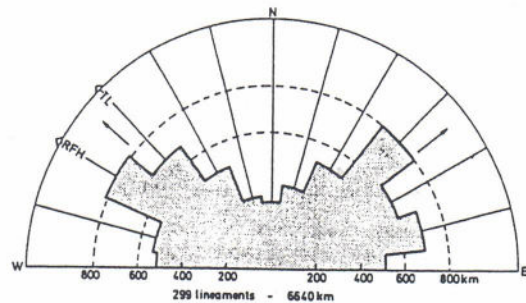


Figure 9 (ref. 7)

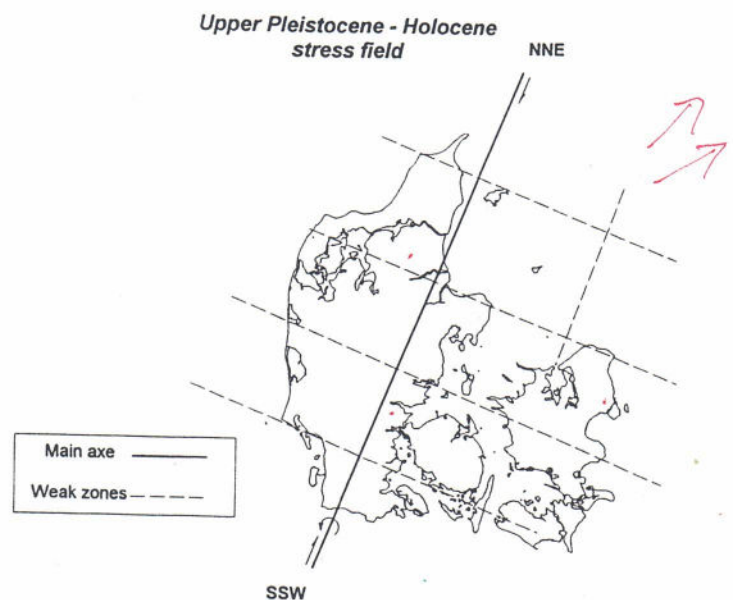


Figure 10

deposited in-between the small blocks. This is an indication that the tilting is still in action. We can follow this tilting zone to the north, where the late Weichselian water-laid and Holocene deposits are absent (figure 12).

It can be argued that the folding and dislocations observed in Store Middelgrund and Rødebanke, could be the result of proglacial deformation at the front of the glacier, as the unit 2 which, is interpreted as a till, is observed only east of this area. The width of the homogeneously folded sheet of sediments however, which is 10 km in some places can not be explained by ice margin deformation. A regional tectonic regime created by the block movements of the area on the other hand could explain such kind of deformations. Also, near Anholt and Læsø islands, a large area is found in which the Quaternary deposits are strongly dislocated. These areas are situated in the limits or inside the Sorgenfrei - Tornquist zone. Earthquakes recorded in the Kattegat area, indicate that this zone, or at list a part of it, is still active.

The same tilting can also be observed in the northern part of Jutland where lateglacial and postglacial marine deposits are founded on the eastern coast in a much higher level than on the west coast. At the same time the inverse pressure in the SSW - NNE axe, uplifting the block more in the northern part than in south. This complicate movement which explains the spatial appearance of the formations, indicating at the same time limits between blocks. The tilting that occurs more strongly to this northern block than to others southern, explains the diverse behavior of the blocks under the same broad stress tectonic regime (figure 13).

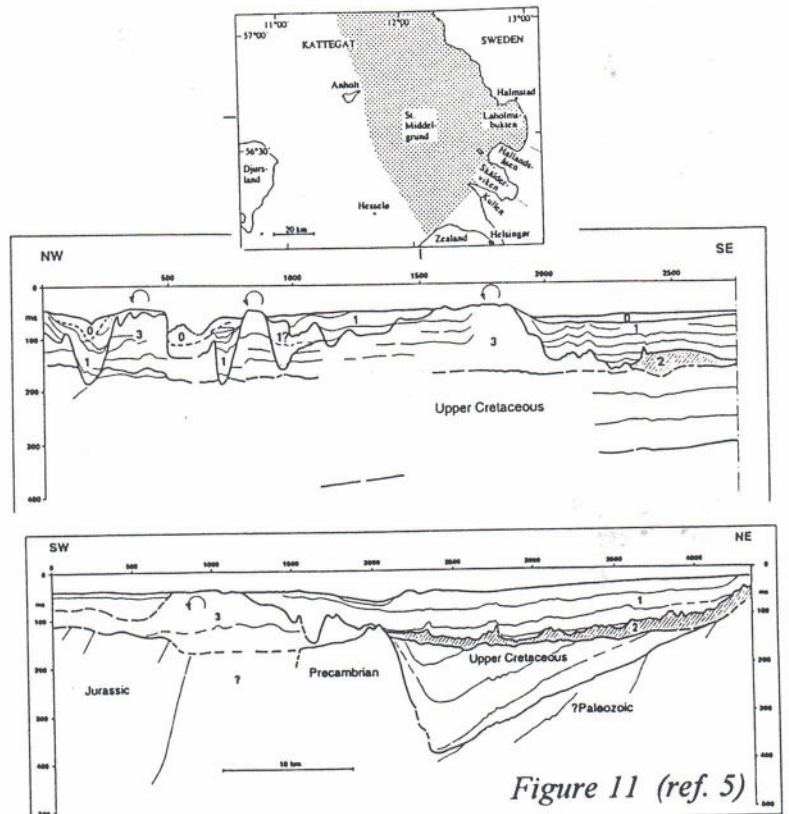


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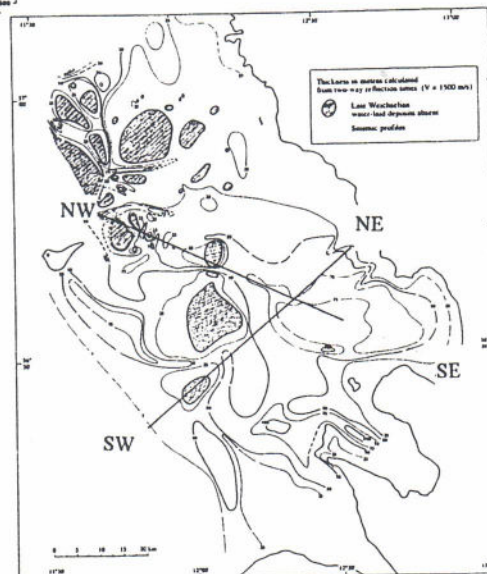


Figure 12 (ref. 5)

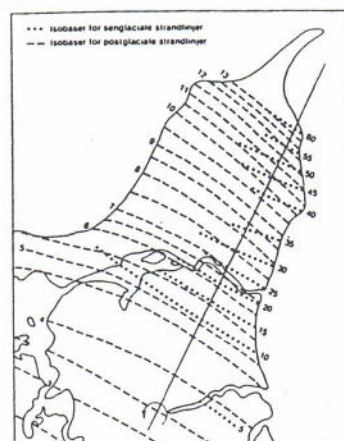


Figure 13 (ref. 3)

Areas of surface deformation have been superimposed in a map in order to determine the relations between them. It is obvious (figure 14), that the spatial distribution of these places determinate parallel lines in the WNW - ESE direction which is also the main block development direction. These lines, at the same time, determinate the limits of these blocks. It can be argue that some of these structures have been produced as a result of proglacial deformation as they are situated on ice margins. Indications of neotectonic action in some of these places (Lønstrup Klint, Vendyssel H. Lykke-Andersen 1981), lead us to the conclusion that the main deformation has a tectonic origin. The main major inverse stress field of SSW - NNE direction combined with the existing tilting, produce the movements between the blocks and create secondary stress fields responsible for the observed structures. It is of course intresting to distinguish how much the ice has affected these structures as its movement have been determinated by the locals tectonic stress fields.

The earthquakes epicentres of the area outline a square around the Danish basin with the same more or less well known directions SSW - NNE and WNW - ESE. This square tectonic unit is limited NW by the Skagerrak sea, NE and SE by the Fennoscandian border zone and SW by the Ringkøbing - Fyn High structural

horst. As we can see there is a concentration of earthquakes epicentres in the Kattegat sea area especially inside the Tornquist zone. Earthquakes epicentres exist as well in other places inside the basin. This is an indication that we have neotectonic activities not only at the boundaries of the basin, but within the basin as well (figure 15). Local stress fields created by a broader one, move the blocks and produce earthquakes as a result. Due to the relatively low activity, it is not easy to determinate the exact block limits and the local stress fields in the area.

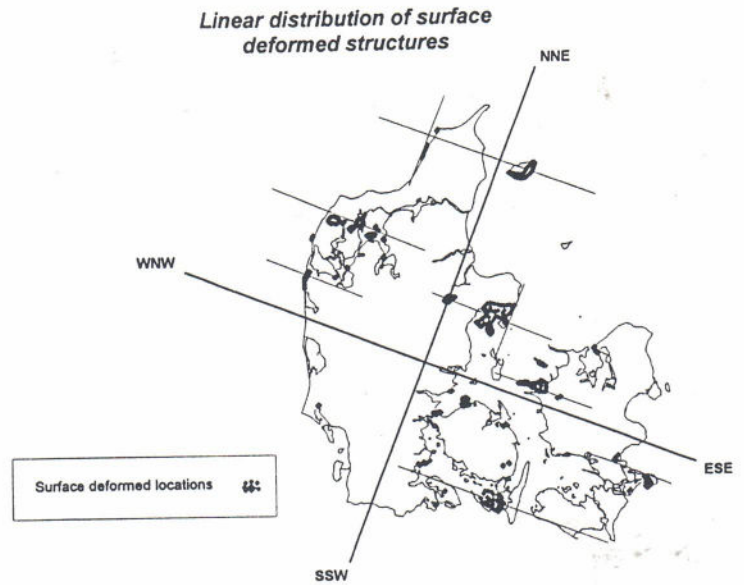


Figure 14

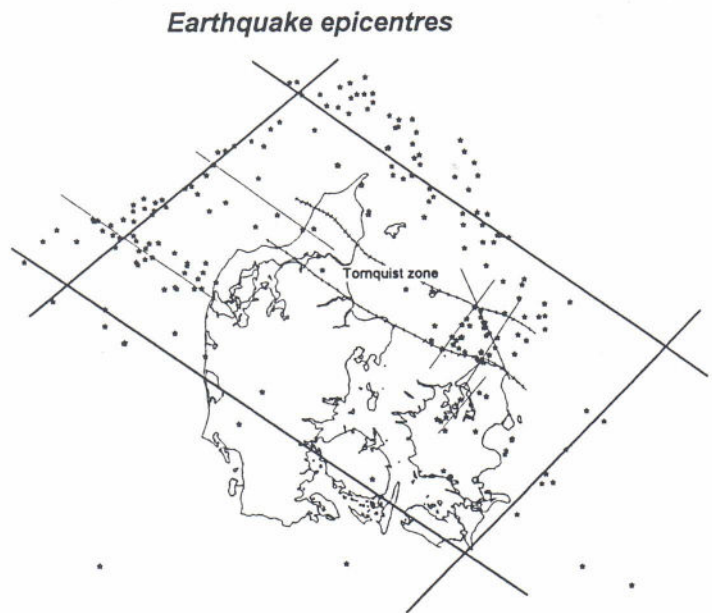


Figure 15

Conclusion

Since Lower Tertiary, the broad area of Danish basin was affected by three main stress fields. The first took place during Lower - Middle Tertiary and is characterised by a major inverse pressure of SSW - NNE direction combined with a tilting which plunged the area through WNW. The second one, took place during the Upper Tertiary, tilting the area around a ESE - WNW axe and plunged it through SSW. The third and final stress field, which has almost the same features as the first one (Lower - Middle Tertiary), started during the Quaternary and continues its activity until the recent time.

All the three fields used the same weak zones in order to deformate the area. These weak zones consist of linear parallel structures in two main directions SSW - NNE and ESE - WNW. These parallel structures create a sequence of individual blocks elongated in the ESE - WNW direction. These blocks uplifted, subducted and tilted during the active periods in diverse ways. It seems that some of them, especially the ones situating close to the basin margins, behave more active than some others. Simultaneous movements between them, created local stress fields which are responsible for structures, appearing at their boundaries.

Close relations between these subsurface structures and glacial surface activity, lead us to the conclusion that the ice has been manipulated by the existing tectonic pattern which was active during ice periods. A very good correlation between the lineament surface pattern, e.g. drainage network and the main tectonic directions of the area, together with the existence of earthquakes epicentres along the same lines, are clear indications of neotectonic activity.

The Danish area is considered as non-active, in relation to others areas in the world placed at the margins of the main tectonic plates. As a geological unit however, this area consists of a structural basin situated next to an old continental shield. It is reasonable to expect therefore, that there is an activity between the boundaries of these units, due to the broader tectonic forces produced by the plate tectonic movements.

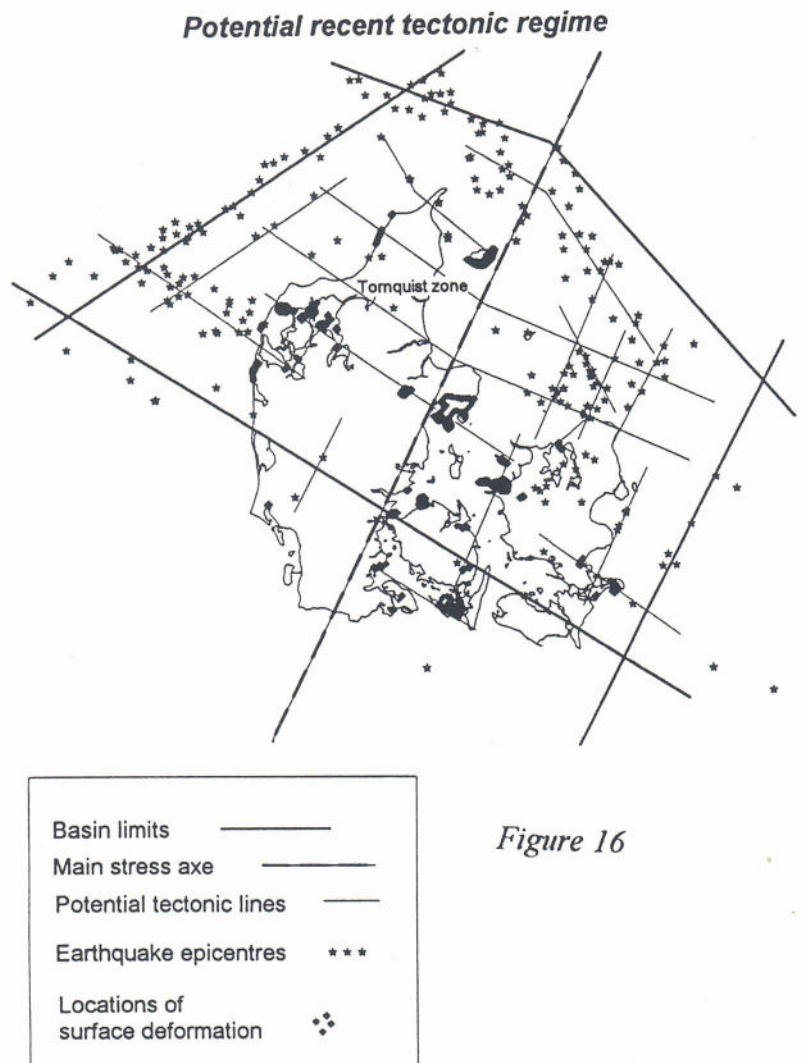


Figure 16

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