DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/44

Faults and joints in chalk, Denmark: The Thisted Dome

Lena Thrane and Kim Zinck-Jørgensen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

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The fault and fracture pattern in the Thisted Dome has been established from stereoscopic aerial photographs covering the entire dome and from investigations of chalk quarries and natural outcrops in the area in terms of establishing the fracture pattern and characteristics of the entire area. Quantitative data, such as orientation (strike/dip) of fractures and fracture density information (line samples) from the area are presented in this report.

The research is part of the JOULE III research project: Equivalent volume modelling of dual porosity dual permeability hydrocarbon reservoirs. The objective of the research is to develop techniques for optimising the production from fractured dual porosity, dual permeability hydrocarbon reservoirs. This research is a contribution to the geological fracture characterisation.

Chalk in northern Jylland

The Upper Cretaceous and Danian of the Danish area are dominated by very pure, largely biogenic limestones. In the Early Maastrichtian global high stand all of the danish territory was transgressed as the culmination of the period of 35 mill. years (Cenomanian- Maastrichtian) during which the chalk was deposited in a shallow seaway running from the Cretaceous Atlantic in the west to Poland in the east, bordered by the Fennoscandian Precambrian Shield and the Middle Europe islands (fig. 1; Håkansson et al. 1974). The near-shore areas were dominated by greensands and biocalcarenites passing into biomicrites or chalks towards the basin. In the earlier part of the Danian the marine accumulation was largely confined to the Danish Basin (Håkansson & Thomsen 1979) and the Central Graben in the present North Sea. Chalks in northern Jylland are basinal and occupies regions with salt induced highs as well as fault controlled inversion structures - much like the situation in the Central Graben.

The inversion took place during the Cretaceous and Early Tertiary along the Fennoscandian Border Zone, and due to subsequent regional Neogene upheaval and intensive Quaternary erosion, the location of the coastline to the north is not known. The chalk level now exposed is the result of up to 1000 metres of Neogene uplift and subsequent erosion (Japsen 1993). Glacial influence is largely erosional in northern Jylland with only local internal deformation of the chalk sequence. The melting of the icesheet, however, has induced horizontal, largely bed paralleling deloading fractures of the near surface part of the chalk sequence.

Maastrichtian and Danian chalks and limestones are exposed in the sub-Quaternary surface in a zone across northern Jylland (fig. 2). Mostly the rocks are covered by glacial and postglacial deposits, but in a series of quarries and natural outcrops the chalks and limestones are readily accessible.

Main lithologies include a more or less continuous spectrum of biogenic carbonate sediments ranging between the two dominant end members, pelagic chalk and bryozoan limestone (Bromley 1979). The insoluble residue is low, suggesting a low influence of terrestrial material. The chalk is intensively bioturbated with distinct burrows indicating deposition in mainly oxic conditions (Ekdale and Bromley, 1984). Sedimentation rate has been fairly high during the Maastrichtian (Håkansson et al. 1974). As a result of low to moderate post-depositional burial most on-shore chalk has suffered surprisingly mild diagenesis and has retained a very high primary porosity.

Except for the low diagenetic levels, Maastrichtian and Danian chalks and limestones in northern Jylland are considered close analogs to the chalk reservoirs in the North Sea.

The Thisted Dome

Introduction

The area between Thisted and Hanstholm occupies the crestal part of a broad, flat salt-induced dome (fig 3). In this dome movements of the deep lying Zechstein salt commenced in Late Triassic time, have been active in the Holocene and may still be going on today (Hansen & Håkansson 1980; Madirazza 1981). As a result of the very late movements, chalk and limestones of Maastrichtian and Danian age are extensively exposed at the surface, in part without a cover of glacial sediments (fig. 3). The topography of the area is dominated by a hemi-circular line of prominent hills, capped by Danian limestones, while inside the hemi-circle Late Maastrichtian chalk is the youngest pre-Quaternary deposit present. The center of the structure is believed to be situated slightly north of Nors Sø (fig. 3).

Limestones in the Hanstholm Hill, on the northern side of the dome, dip gently towards the north, as confirmed by age diferences of the bryozoan limestones at the north- and south-side of the hill, respectively (Hansen & Håkansson 1980). Limestone in the Hjardemål Hill in the north-eastern part of the dome dips towards the northeast, and the area south of the lake Vandet Sø the limestone shows a generel dip towards the south (Andersen 1944). However, the dips rarely exceed 5 degrees.

Stratigraphy

Due to its domal nature the Thisted Dome exposes a wide stratigraphic range of chalk at the surface. Preliminary biostratigraphical investigations indicate that the entire Maastrichtian system may be present, and possibly the center of the structure exhibit chalk of Late Campanian age (E. Håkansson, pers. com. 1996). Similarly a wide range of Danian sediments are exposed in the area, particularly along the northern and eastern perimeter. The basal Danian succession is exposed intermittently all around the dome (Håkansson & Hansen 1979, Hansen 1979). At the northern margin of the structure the Middle Danian zone NP3 is exposed on the beach NE of Hanstholm Hill (Thomsen, 1995), while the Late Danian zones NP8 and NP9 are exposed within the Hanstholm Harbour immediately NW of Hanstholm Hill (Hansen & Håkansson, 1979, Thomsen 1995).

Structural geology

Structural data from the area have been obtained at two scales. The large scale fault pattern of the Thisted Dome has been established from stereoscopic interpretation of aerial photographs covering an area of approximately 400 sq. km, while orientation on the numerous small scale fractures has been determined in outcrops.

Most prominent faults are compatible with the systems of radiating and concentric faults expected over a rising dome. The elongated Danian limestone hills are bounded by faults belonging to a concentric fault system and the hills are separated by wide gabs and intersected by narrow gullies representing a radiating fault system. A more chaotic fault pattern is found in the center of the dome with several fault bounded lakes, among which Nors Sø can be considered a collapse graben.

So far only a single topographically determined fault line has been documented through biostratigraphic investigation; i.e. a relative down-throw in excess of 50 m has been established for the block immediately west of Hanstholm (fig. 3; Hansen & Håkansson, 1980).

The small scale fracture orientation has been determined at three different localities in the Thisted Dome. Thisted Quarry and Nye Kløv are both situated at the rim of the of the dome, in the southeastern and in the eastern part, respectively. Hillerslev Quarry is also situated in the eastern part of the dome but more towards the center of the structure. Strike orientation of fractures measured in these localities are presented as rose frequency diagrams on fig. 3. In Thisted Quarry the ENE-WSW and the NW-SE orientations are easily explained as part of the overall radiating and concentric fault pattern whereas the relation of the N-S fracture orientation is less obvious. At Nye Kløv two orientations are dominating, one is NNE-SSW paralleling the concentric faults pattern, whereas the other, NW-SE, parallels the major faults creating the gabs between the prominent hills both north and south of the locality. The dominating orientations in the Hillerslev quarry are ENE-WSW and NNW-SSE, which are in good accordance with the fault pattern detected in the immediate vicinity of the locality.

Rose frequency diagrams of dip direction from the three localities are presented in fig. 4. The dip direction of fractures in Hilleslev Quarry are clearly pointing away from the center of the dome, whereas both Thisted Quarry and Nye Kløv have fractures which are dipping away from the dome center and a number of fractures orientated more or less perpendicular to the first set.

Locality descriptions

Hillerslev Quarry

The Hillerslev Quarry is an active chalk quarry located immediately southwest of the village Hillerslev in the eastern half of the Thisted Dome (fig. 3). Presently it provides the only good exposure within the central portion of the dome although it is located at some distance from the very center. The size of the quarry is approximately 500 sq. metres. The general tilt in the area is 4 degrees towards ESE.

The chalk (which is used as fertilizer in agriculture) is scrabed of in the bottom of the quarry and this production technicque leaves no good exposures. The quarry is partly surrounded by low quarry walls covered by scree.

A low quarry wall (approximately 4 m high and 45 m long) in the northern part of the quarry has been excavated and described in detail. A number of one inch core plugs from the profile have been sampled, and described and analysed for porosity and permeability. Fracture density and fracture orientation (strike/dip) have been obtained, mainly from the excaveted profile, and supplemented with fracture orientation measurements from several locations in the quarry.

Stratigraphy and lithology

The chalk in the quarry is of Late Maastrichtian age, belonging to the *humboldtii-stevensis* Zone (Brachiopod zone 9, E.Håkansson pers. com 1996). It is a soft, weakly cemented mudstone/wackestone, composed almost exclusively of coccolithic material with subordinate amounts of skeletal material (foraminifera, bryozoans, echinoderms, molluscs) and a low content of silica, clay minerals and pyrite.

Horisontal bedding of the chalk is indicated by a slightly darker marly chalk and discontinuous layers of flint. The flint layers are traceable over larger areas and they are usefull as marker horizons. The individual beds occur as sheet like deposits with a lateral extension exceeding the length of the profile investigated.

Porosity and permeability

Porosity and permeability have been determined from a number of one inch core plugs. The average porosity is 47 % (with a range from 44 % to 52 %) and the average permeability is 8.1 mD (ranging from 5.1 mD to 13.4 mD).

The one inch core plugs and fracture data was sampled along the same line and the possible linkige between the variation in porosity and permeability and the position of fractures was therefore investigated. However, low as well as high values of porosity and permeability are found associated with fractures and no consistency could be detected.

Thisted Quarry

The Thisted Quarry is an active chalk quarry at the southeastern margin of the dome (fig. 3). The quarry exposes the Maastrichtian/Danian boundary. In the southern part of the quarry, bryozoan limestone of Early Danian age rests on the chalk on a partly thrusted contact. The general tilt in the area is towards SE.

The chalk (which is used as fertilizer in agriculture) is scrabed of in the bottom of the quarry, leaving no good exposures. The quarry is partly surrounded by low quarry walls which are covered by large amounts of scree. A small part of the southern quarry wall (in the Maastrichtian chalk sequence) was excavated for this investigation and fracture orientation (strike/dip) was measured.

The age of the Maastrichtian chalk just below the boundary belongs to the Brachiopod Zone *stevensis-chitoniformis* (Brachiopod zone 10) (Håkansson & Hansen, 1979).

Nye Kløv

The locality is a small abandoned chalk pit in a postglacial fault-generated sea cliff in the eastern part of the Thisted Dome (fig. 3). The entire cliff is approximately 20 m high; a vertical section of 9 m was excavated for this investigation. The section includes the Maastrichtian/Danian boundary, which here is marked by a thin lightgrey marl layer of earliest Danian age (Håkansson & Hansen, 1979). The general tilt of the sequence is towards the E, away from the dome center. Data on fracture orientation (strike/dip) was collected from the profile.

Stratigraphy and lithology

The lowermost 4 m of the excavated profile is of Maastrichtian age and can be characterised as a burrowed massive chalk mudstone. The Maastrichtian chalk is followed by a soft, boundary clay layer (Kjølby Gaard Marl) which is microconglomeratic and smeared, and contains small angular as well as rounded chalk clasts. The Kjølby Gaard Marl is characterised as burrowed laminated argillaceous chalk mudstone.

In the Danian sequence the bryozoan content gradually increases upwards, culminating in a few metres of Bryozoan limestone (Birkelund & Håkansson 1982). The lowermost 3 m of the Danian sequence is characterised as burrowed laminated argillaceous chalk mudstone followed by burrowed massive chalk wackestone (coarsegrained skeletal material dominated by bryozoan fragments). Apart from a significant bryozoan content in the higher parts of the Danian sequence, macrofossils in general are comparatively rare in the rocks exposed at Nye Kløv.

Nodular flint bands are found throughout the Maastrichtian part of the sequence whereas in the Danian part the flint is mainly developed as continuous layers.

Both the uppermost Maastrichtian and the Lower Danian chalk of Nye Kløv is totally burrowed by *Thalassinoides*, *Zoophycos*, *Chondrites* and traces of other organisms. The faunally depauperated lowermost Danian marly chalk is totally bioturbated as well, and *Thalassinoides*, *Planolites* and *Chondrites*-like trace fossils are present here (Ekdale & Bromley, 1984).

The age of the Maastrichtian chalk just below the boundary belongs to the youngest part of the Brachiopod Zone *stevensis-chitoniformis* (Brachiopod zone 10) (Håkansson & Hansen, 1979; Surlyk, 1984; Johansen, 1989). The Danian part of the succession comprises NP1 and NP2 (Coccolith Zones) (Håkansson, Kjaer & Thomsen, 1996).

Porosity and permeability

In the Maastrichtian part of the sequence the average porosity is 45 % (with a range from 42 % to 49.5 %) and the average permeability is 8.6 mD (ranging from 2.5 mD to 15 mD).

The Danian part of the sequence (excluding the Kjølby Gaard Marl) can be divided in to two sections. The lowermost Danian (argillaceous chalk mudstone) has an average porosity of 39 % (with a range from 31 % to 43 %) and an average permeability of 6.6 mD (ranging from 2.7 mD to 14.5 mD). The succeding, bryozoan-rich Danian sequence has an average porosity of 40 % (with a range from 35 % to 47 %) and an average permeability of 36 mD (ranging from 4.4 mD to 82 mD).

Fracture investigation

Information on fracture orientation (strike/dip) was obtained from all three localities whereas detailed information on fracture density was only obtainable from Hillerslev Quarry.

Orientation

The orientation of the numerous fractures from each locality was measured as strike/dip and subsequently plottet in a Wulff projection as normals to fracture planes and as contours plots. Furthermore, strike has been plottet as rose frequency diagrams. Dip and dip direction has been plotted as histograms for each locality and dip direction as rose diagrams as well.

Based on their dip fractures can be divided into two fairly distinct groups with little overlap: A group of low angle to horisontal fractures, dipping less than 30^{o}, and a group of the much more numerous high angle fractures. The most likely origin of the low angle to horisontal fractures is glacigenic thrusting or simply deloading, which means they are late in origin and less relevant for subsurface conditions. These fractures are not considered further in this investigation.

Hillerslev Quarry

The orientation of fracture in Hillerslev Quarry are widely scattered, although some clustering is evident from the contour plot (fig. 5). A rose frequency diagram of strike (fig. 3, 6a) shows that a high proportion of fractures are oriented ENE-WSW and with NNW-SSE as another important direction. The majority of fractures are steeply dipping with a dominance of almost vertical fractures (fig. 7a). Dip direction of the fracture shows that the majority of fractures are dipping towards the E and SE (figs. 6b, 7b).

Thisted Quarry

The orientation of fractures in Thisted Quarry are similarly widely scattered (fig. 8). A rose frequency diagram of strike (fig. 3, 9a) shows that NNW-SSE to N-S is an important direction as well as ENE-WSW direction. The majority of fractures are equally steeply dipping with a clear dominance of vertical to near vertical fractures (fig. 10a). Dip direction of the fractures show a more scattered distribution with a great number of fractures dipping in the southeasterly direction, but with a fair number dipping towards W and N (figs. 9b, 10b).

Nye Kløv

The orientation of fractures can be divided into two dominating directions, NNE-SSW and NW-SE (fig. 12a). The majority of fractures are equally steeply dipping with a clear dominance of vertical to near vertical fractures (fig. 13a). Dip direction of fractures (figs. 12b, 13b) show that the majority of the NNE-SSW striking fractures are dipping towards the ESE, whereas the NW-SE striking fractures are dipping almost equally towards the NE and SW.

Spacing of fractures

A horisontal line sample profile, approximately 31 metres long, was sampled from the excavated quarry wall in Hillerslev Quarry. As the majority of fractures are steep to very steep with a dip of 65° or more the horizontal line sampling employed is considered to be at a sufficiently high angle to the overall fracture orientation. In addition to the position of the fractures on the line the orientation (strike/dip) of each fracture has been determined. The density of fractures is evident from the line sample profile (fig. 14) where each measured fracture is marked by a vertical line.

The fractures have been divided into two sets according to their orientation and each set has been analysed individually. Coefficient of variation (CV) of the density for each subdirectional set of fractures has been calculated. CV values are 0.8 and 0.9 for the two sets indicating that the density of fractures are anticlustered approaching a random spacing (CV = 1 is random spacing). The close approximation to a random spacing of fractures is further confirmed by the spacing-frequency diagrams presented in fig. 15 where the density distribution of each subdirectional fracture set is close to straight lines (fig. 15a) indicating a negative exponential distribution for the two datasets investigated.

The histogram of spacing distribution for the two fracture sets (fig. 15b) show that the great majority of fractures are densely spaced.

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List of figures

Figure 1: Palaeogeographic map of Central Europe and the North Sea area showing the maximum extension of the sea during Late Cretaceous. The map also shows the present-day extra-Alpine outcrops of chalks and related facies and areas with Late Cretaceous inversion. (Modified from Scholle, 1974; Hancock, 1975 and Ziegler, 1990).

Figure 2: Sub-Quaternary geological map of Denmark. FF: Fjerritslev Fault; STZ: Sorgenfrei-Tornquist Fault Zone; BF: Børglum Fault; T: Thisted Dome. (From: Håkansson & Surlyk, in press)

Figure 3: Geological map of the Thisted Dome. A rim of Danian sediments surrounds Maastrichtian chalk. Rose frequency diagram of strike of fractures from Hillerslev Quarry, Thisted Quarry and Nye Kløv are included.

Figure 4: Geological map of the Thisted Dome. A rim of Danian sediments surrounds Maastrichtian chalk. Rose frequency diagram of dip direction of fractures from Hillerslev Quarry, Thisted Quarry and Nye Kløv are included.

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Figure 7: Orientation/frequency histograms of fracture orientations from Hillerslev Quarry. a) dip, b) dip direction.

Figure 8: Stereographic projection (Wulff, lower hemisphere) of fracture orientations in Thisted Quarry. a) normals to fault planes, b) contour plot. Number of measurements is 51.

Figure 9: Rose frequency diagrams of fracture orientations from Thisted Quarry. a) strike, b) dip direction.

Figure 10: Orientation/frequency histograms of fracture orientations from Thisted Quarry. a) dip, b) dipdirection.

Figure 11: Stereographic projection (Wulff, lower hemisphere) of fracture orientations in Nye Kløv. a) normals to fault planes, b) contour plot. Number of measurements is 53.

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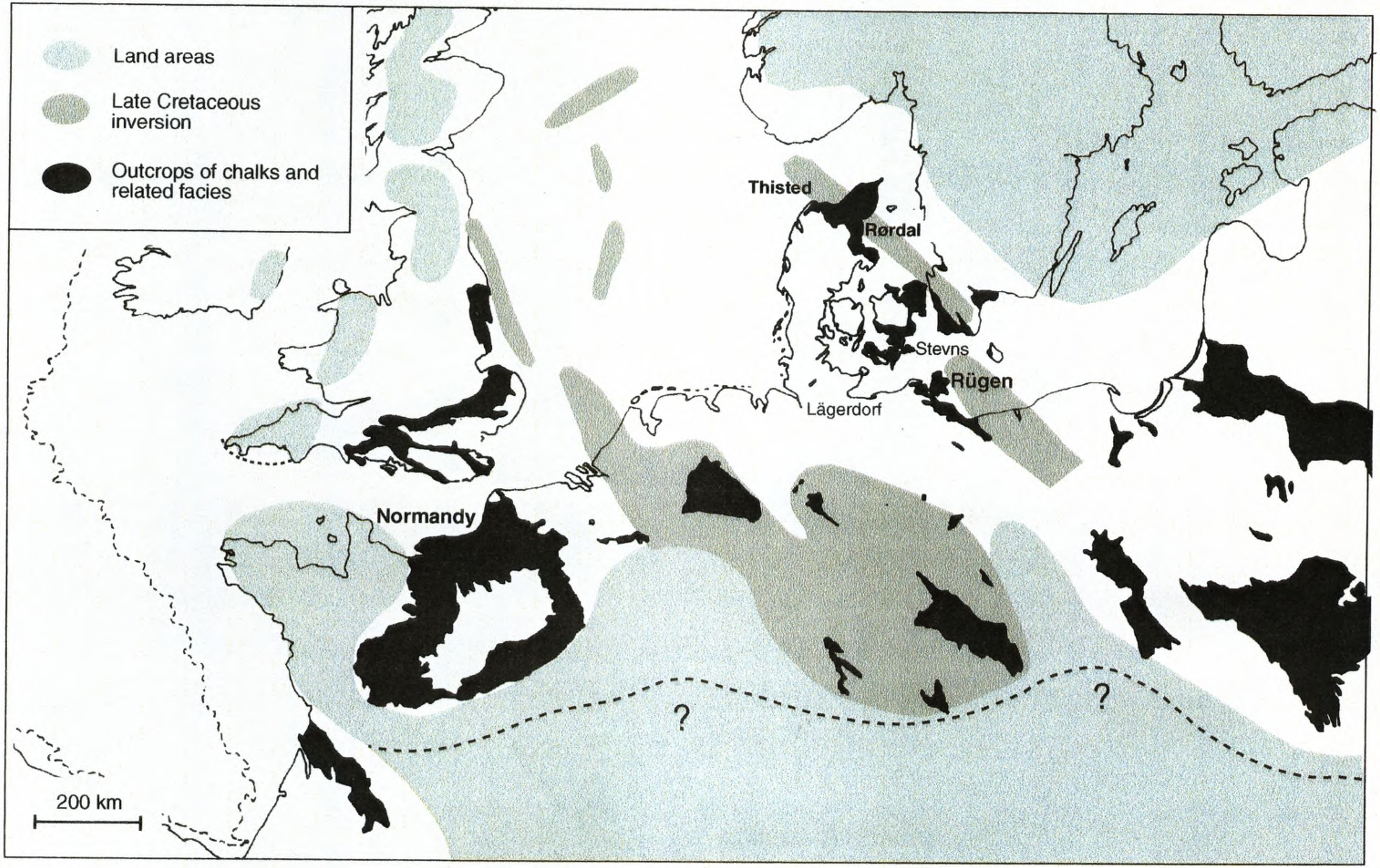
Figure 14: Horisontal line sample profile from Hillerslev Quarry. Fractures are marked by vertical lines.

Figure 15: Density distribution of fractures in line the sample from Hillerslev Quarry. Fractures have been divided into two sets based on their orientation. a) Spacing versus cummulative number showing almost straight lines for both subdirectional fracture sets on a log-linear plot. b) histogram of spacing versus frequency for the two fracture sets.



Land areas
Late Cretaceous inversion
Outcrops of chalks and related facies
Thisted
Rørdal
Stevns
Rügen
Lägerdorf
Normandy
?
?
200 km

Figure 1

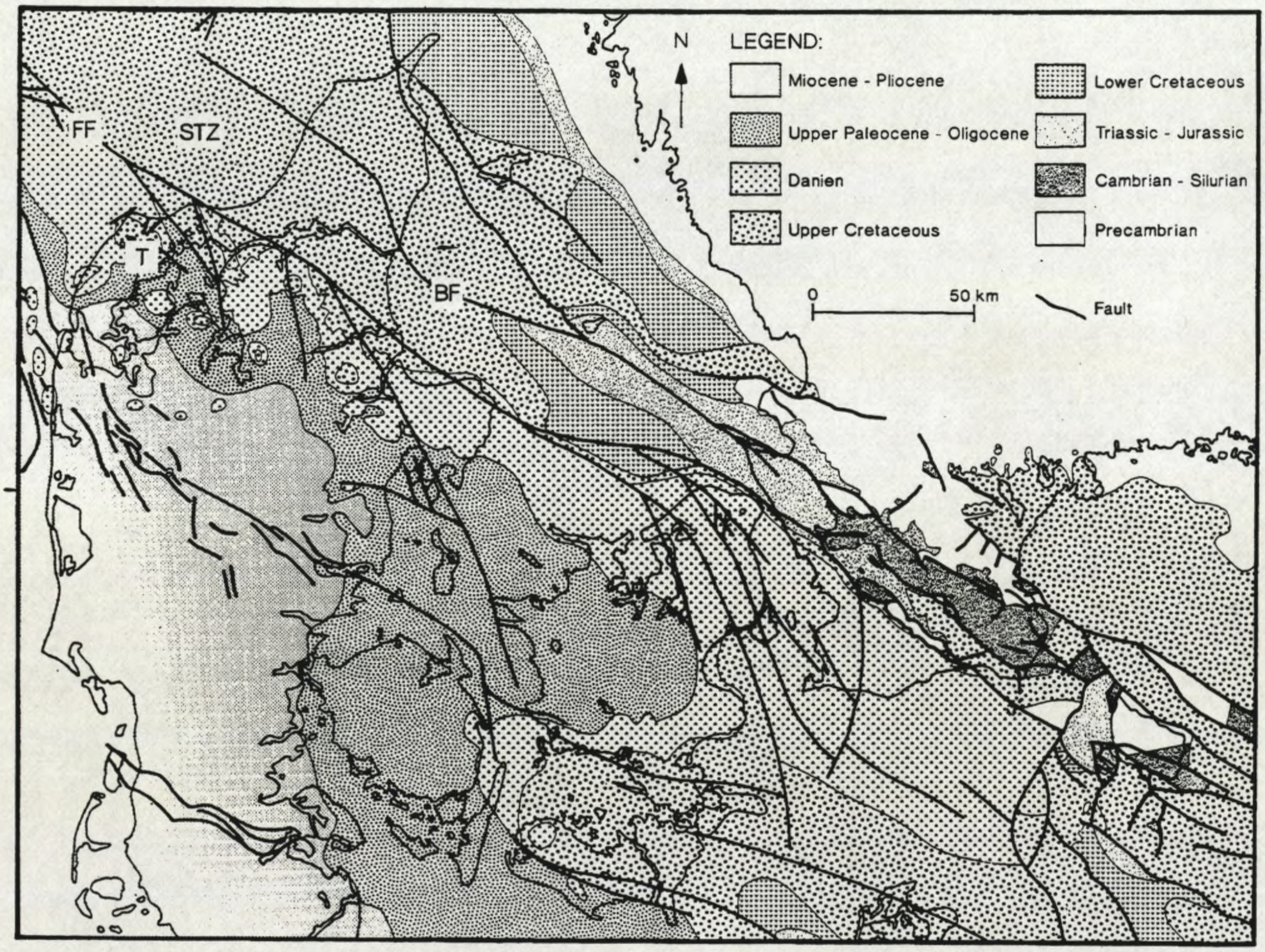

FF
STZ
T
BF
N
LEGEND:
Miocene - Pliocene
Upper Paleocene - Oligocene
Danien
Upper Cretaceous
Lower Cretaceous
Triassic - Jurassic
Cambrian - Silurian
Precambrian
0
50 km
Fault

Fig. 2

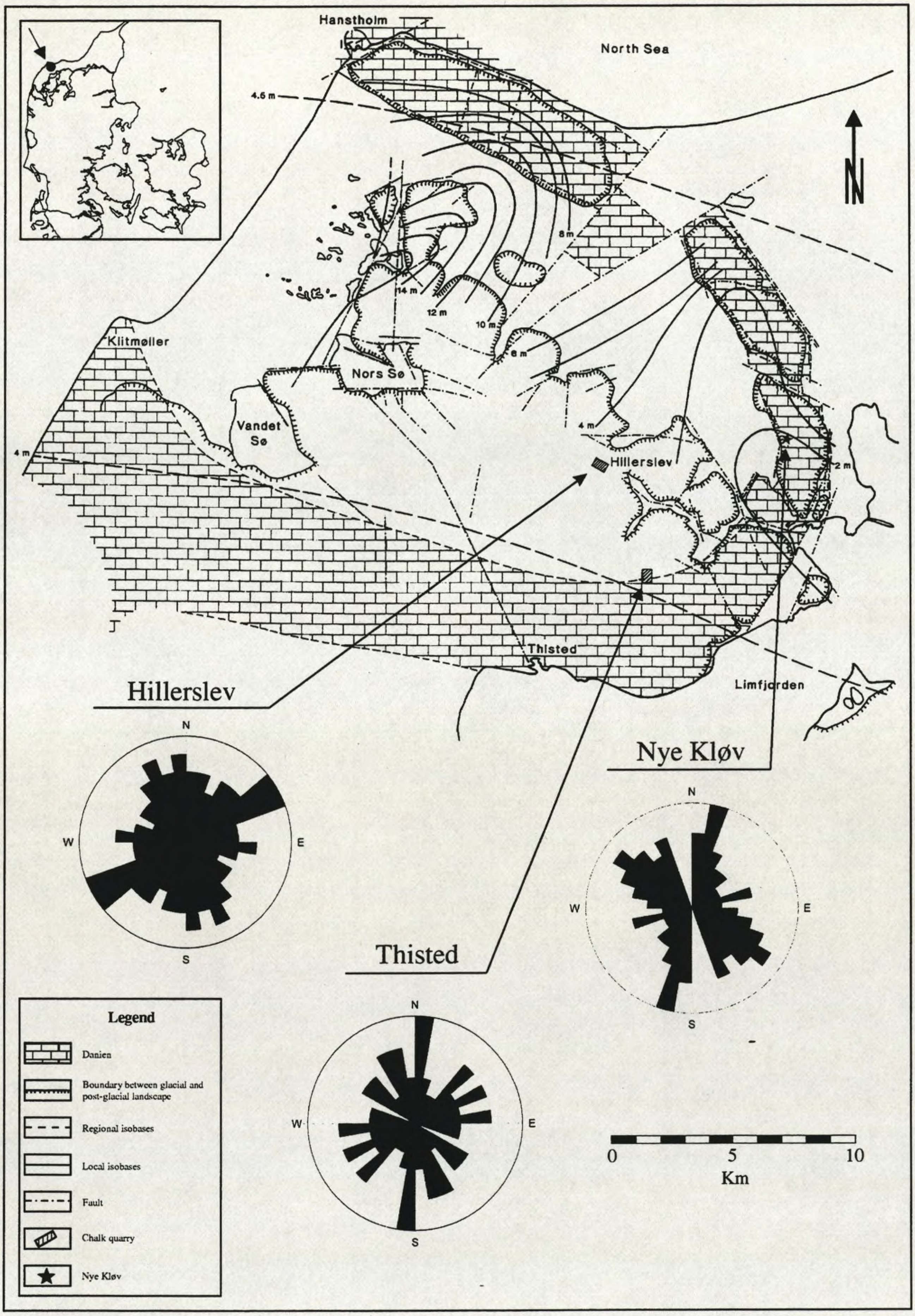
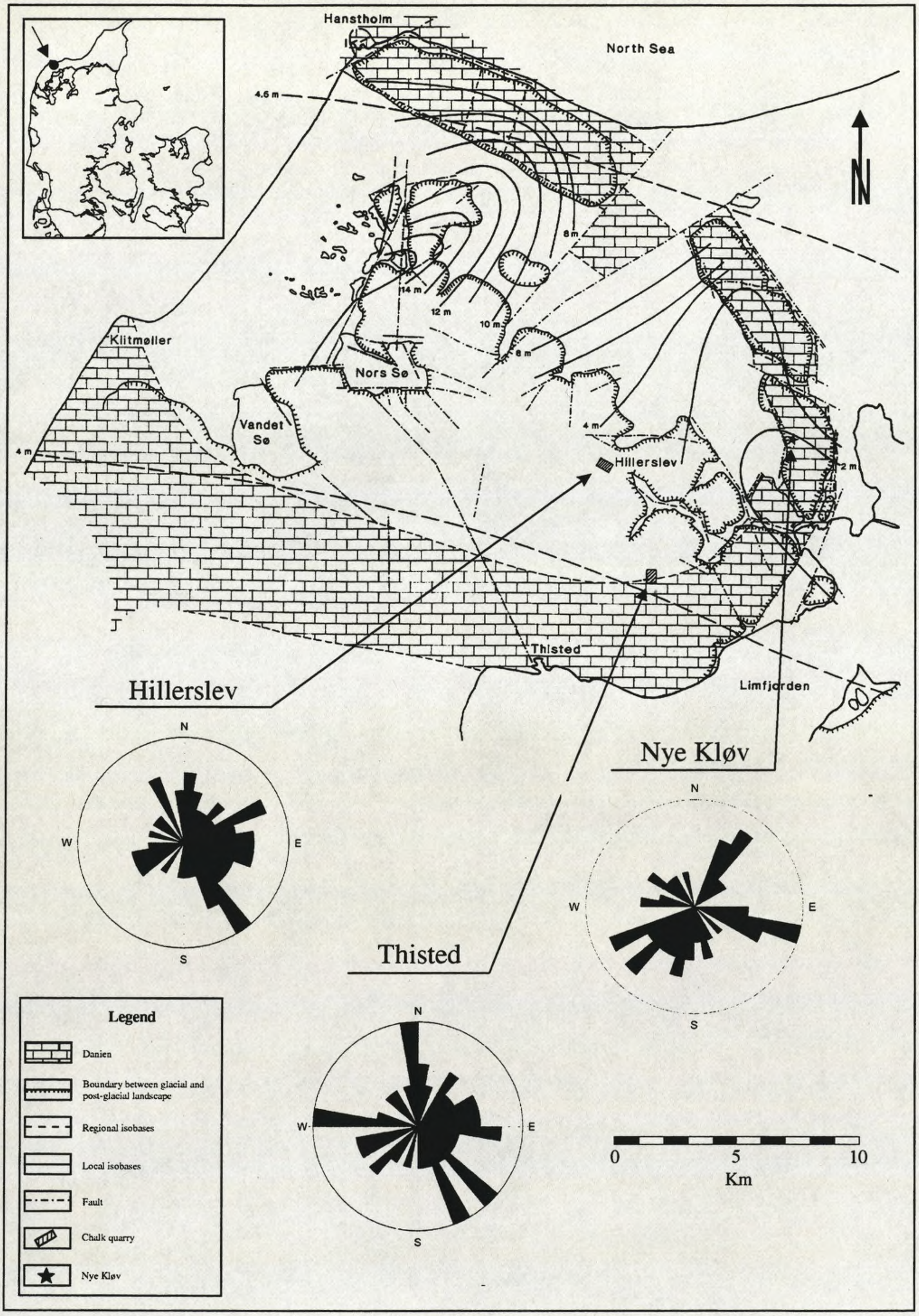

Hanstholm
North Sea
4.6 m
8 m
14 m
12 m
10 m
6 m
4 m
2 m
Klitmøller
Nors Sø
Vandet Sø
4 m
Hillerslev
Thisted
Limfjorden
N
Hillerslev
Nye Kløv
Thisted
N
W
E
S
Legend
Danien
Boundary between glacial and post-glacial landscape
Regional isobases
Local isobases
Fault
Chalk quarry
Nye Kløv
0
5
10
Km

Fig. 3


Hanstholm
North Sea
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Hillerslev
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Thisted
Limfjorden
Hillerslev
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Legend
Danien
Boundary between glacial and post-glacial landscape
Regional isobases
Local isobases
Fault
Chalk quarry
Nye Kløv
0
5
10
Km

Fig. 4

Hillerslev 1 & 2

Wulff projection

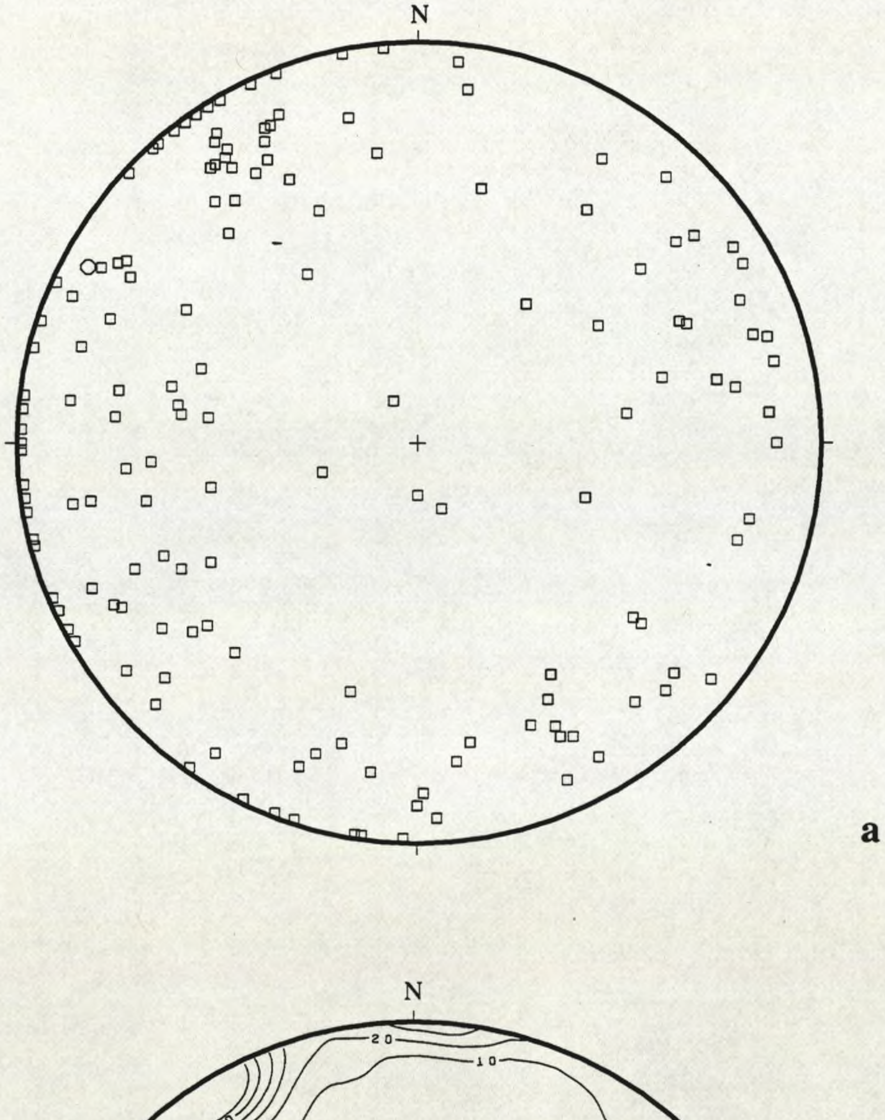
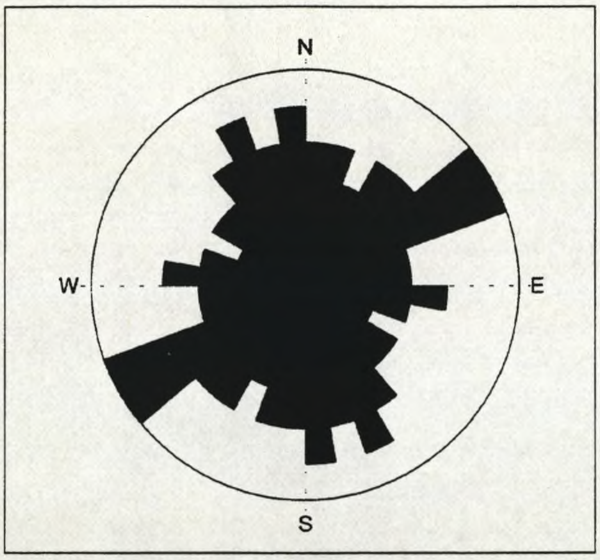


Fig. 5

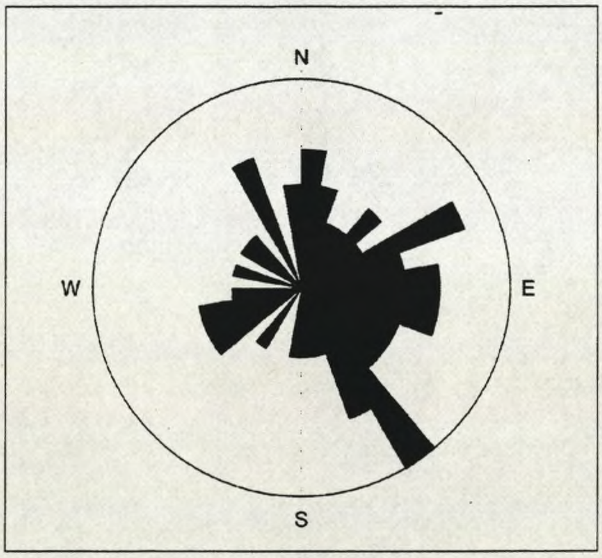
Hillerslev

Strike



a

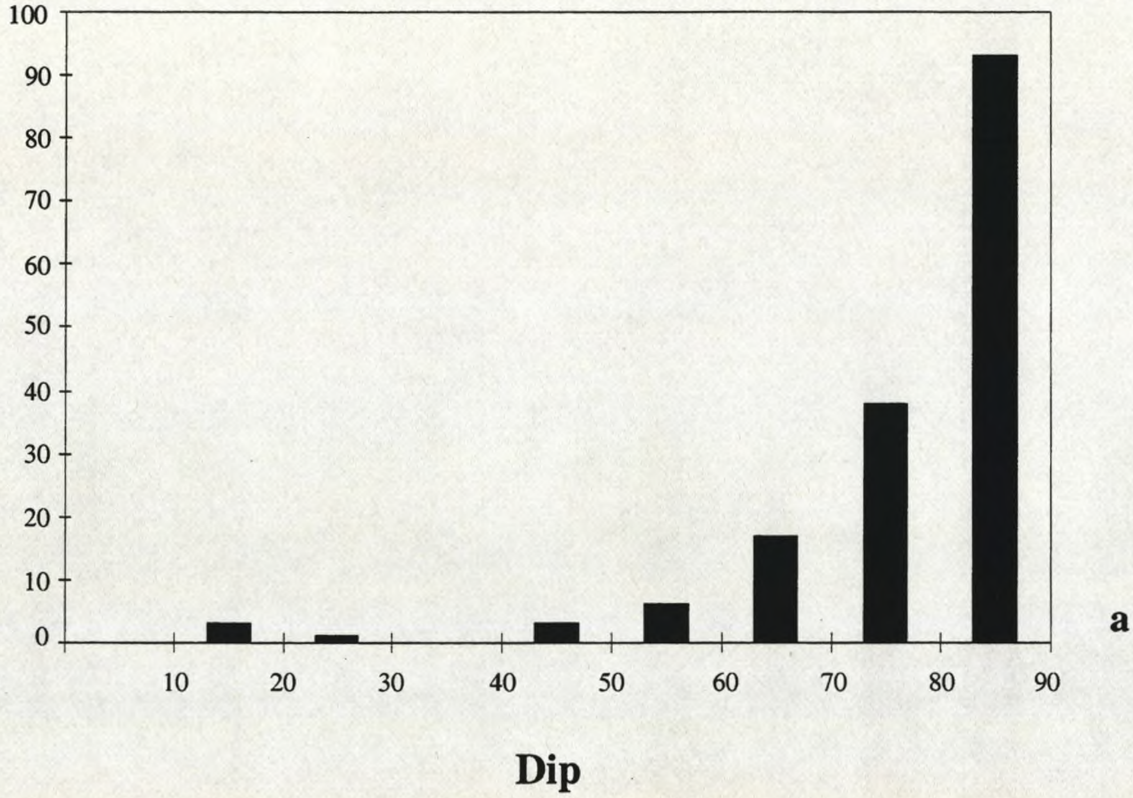
Dipdirection



b

Fig. 6

Hillerslev



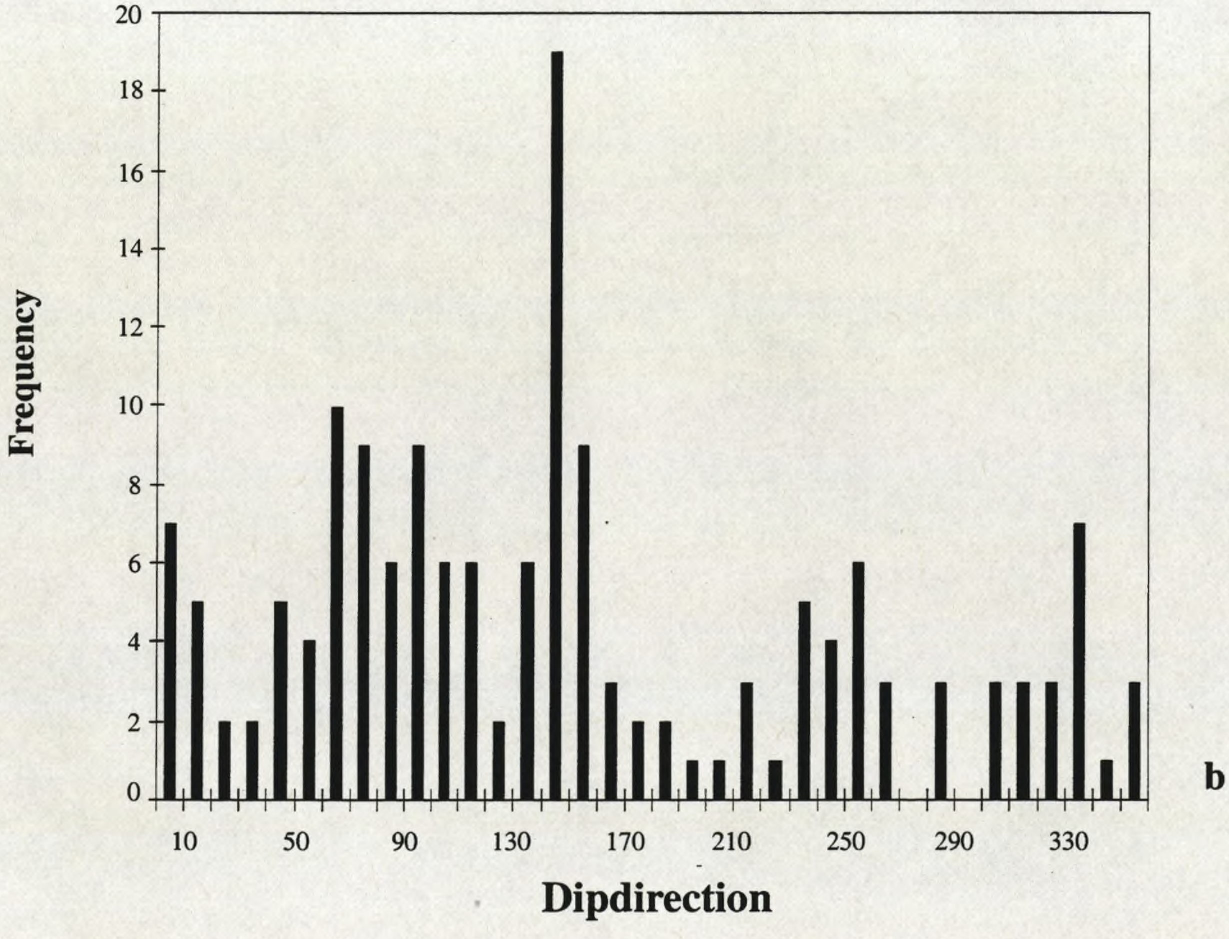


Fig. 7

Thisted

Wulff projection

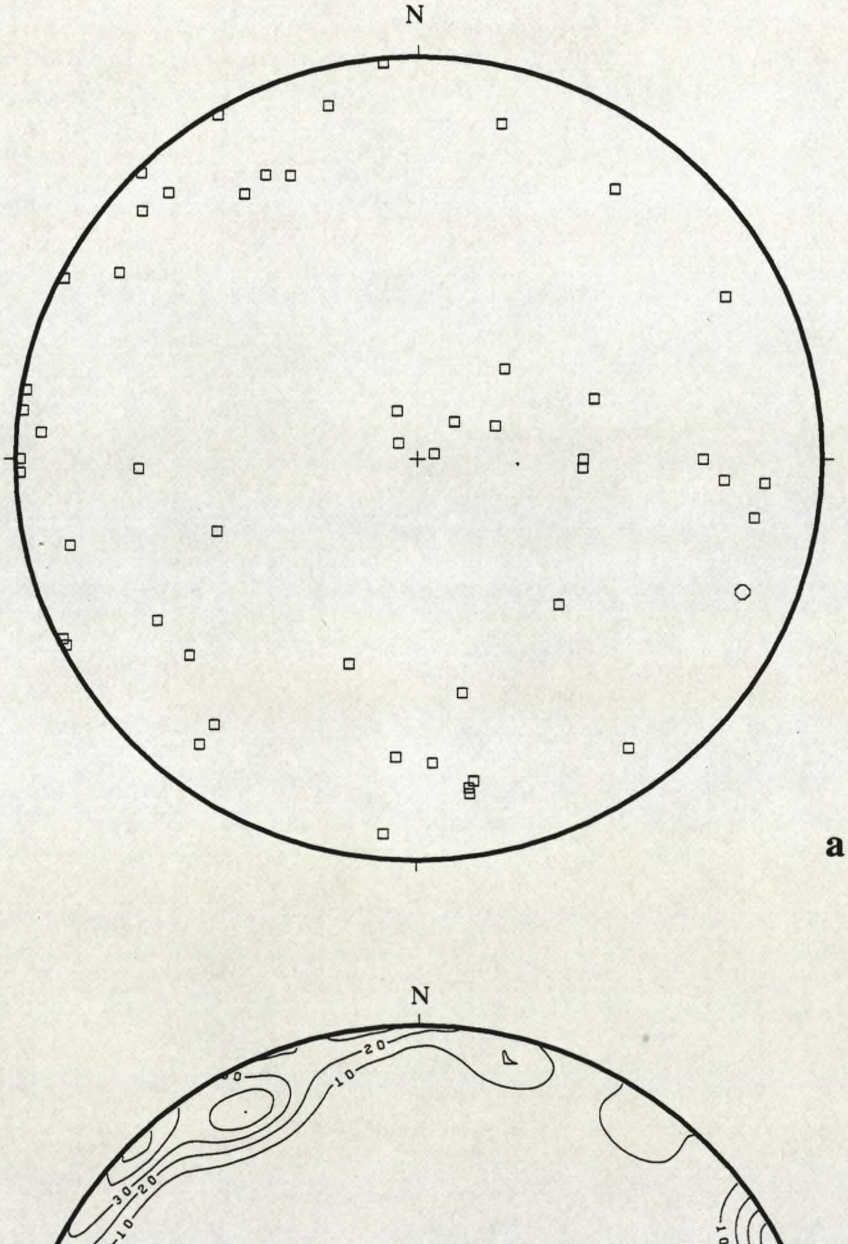
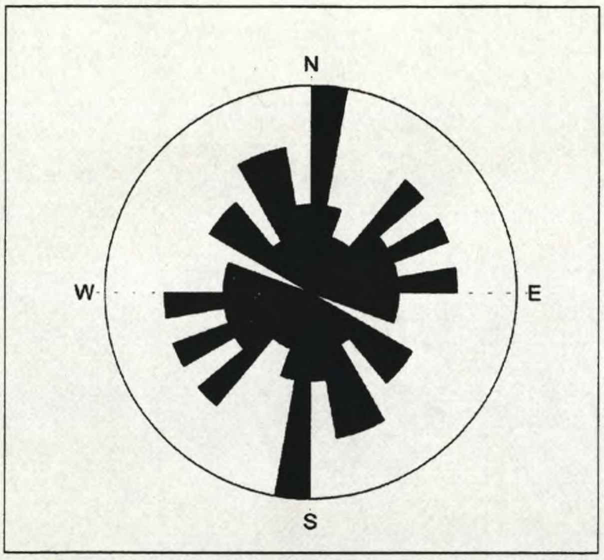


Fig. 8

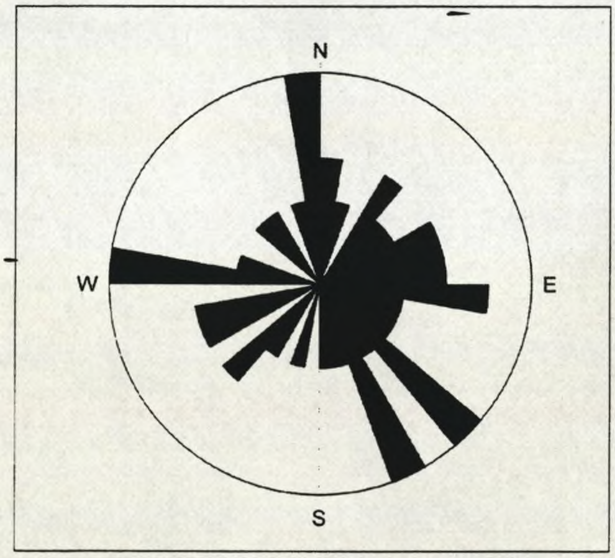
Thisted

Strike



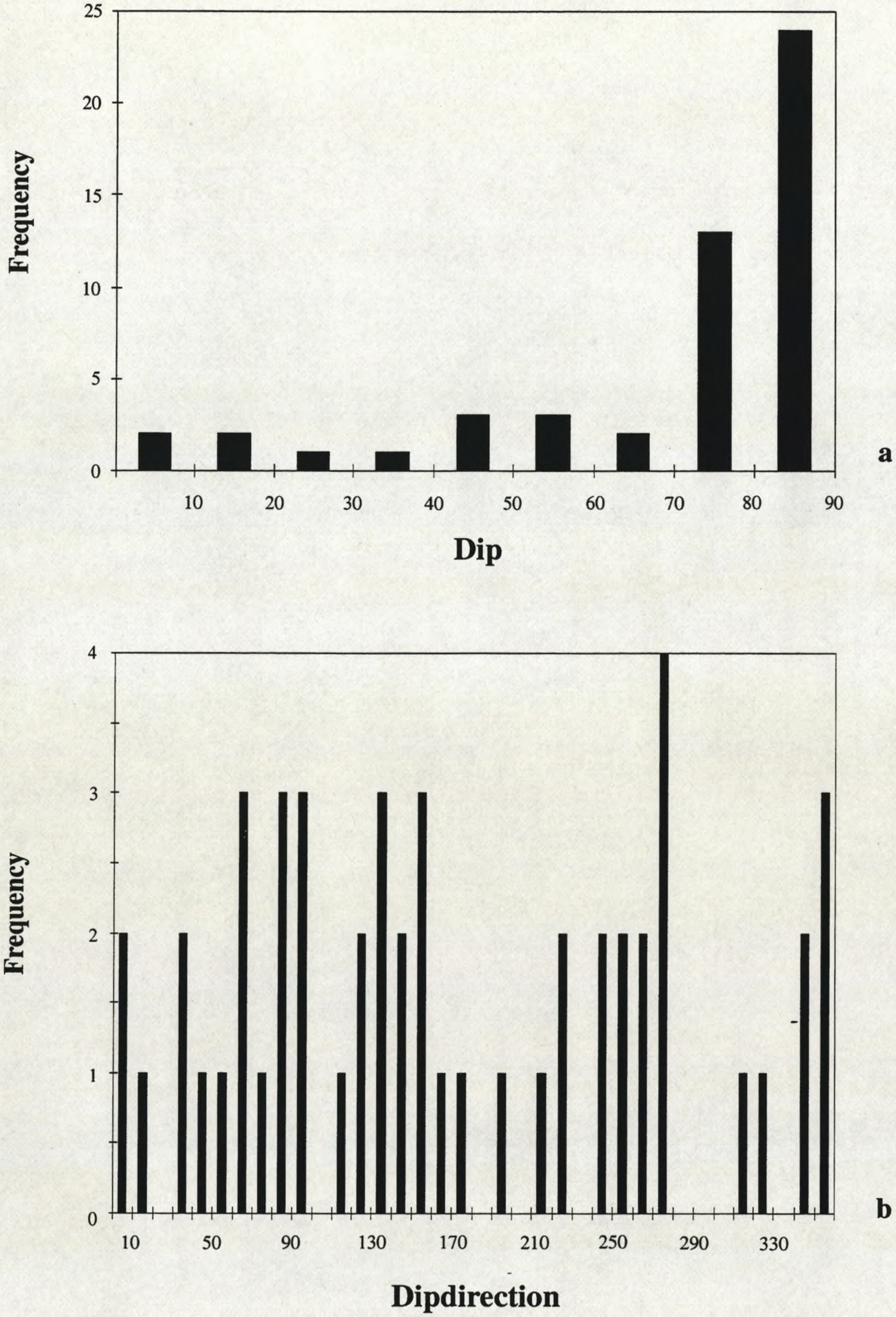
a

Dipdirection



b

Fig. 9

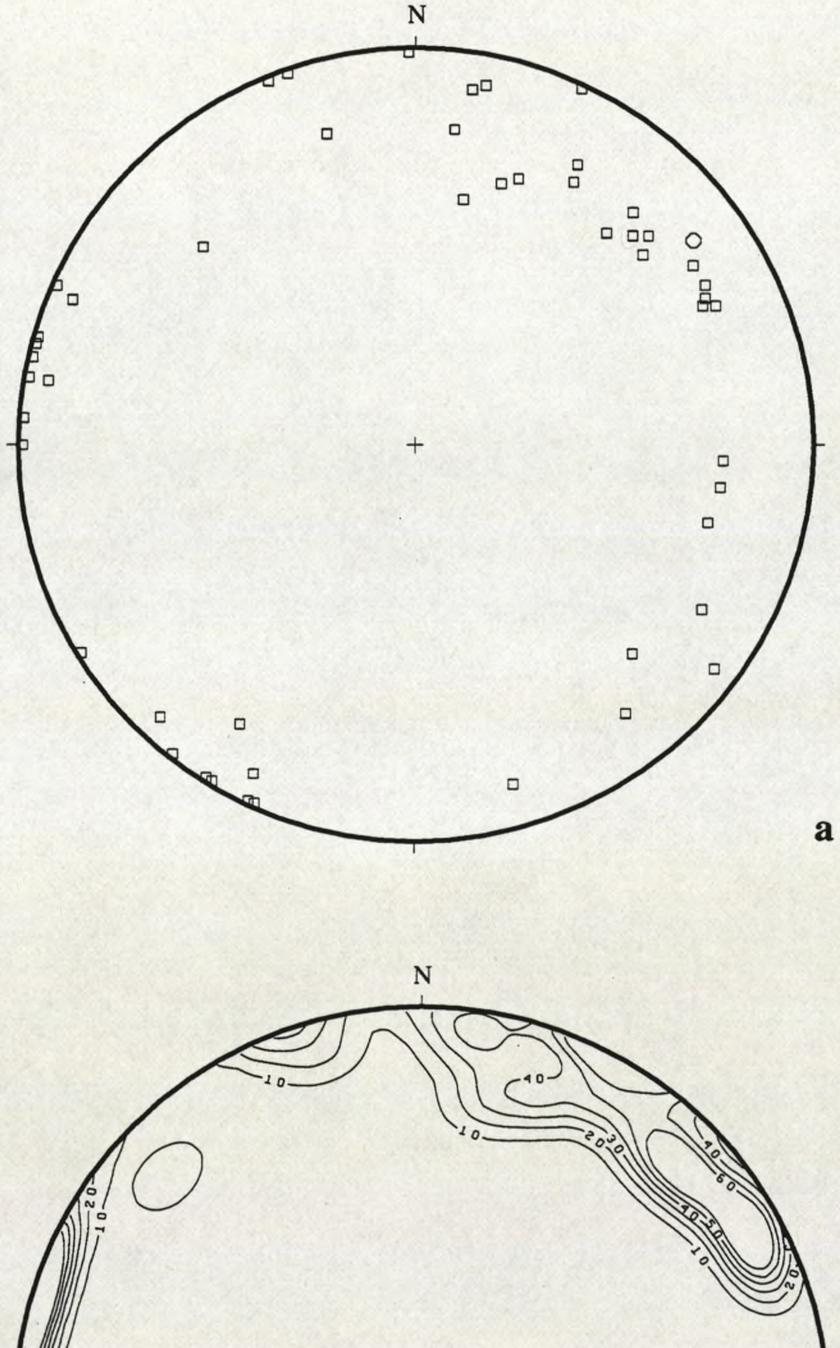


Thisted

Fig. 10

Nye Kløv

Wulf Projection

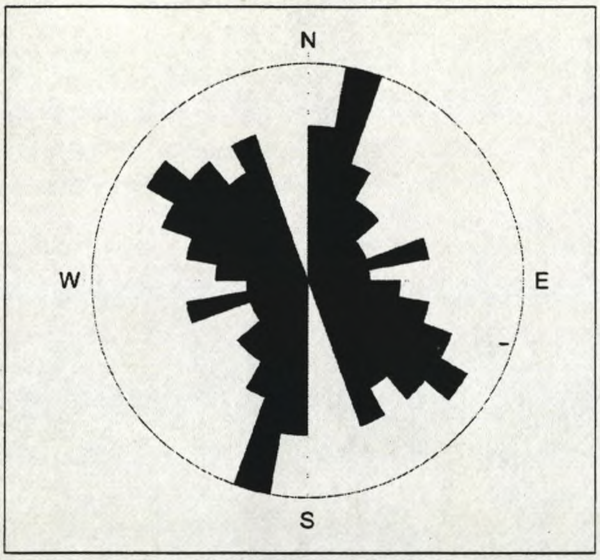


b

Fig. 11

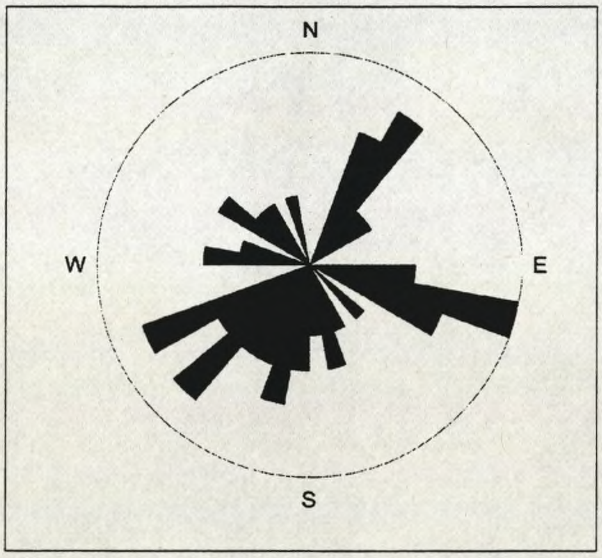
Nye Kløv

Strike



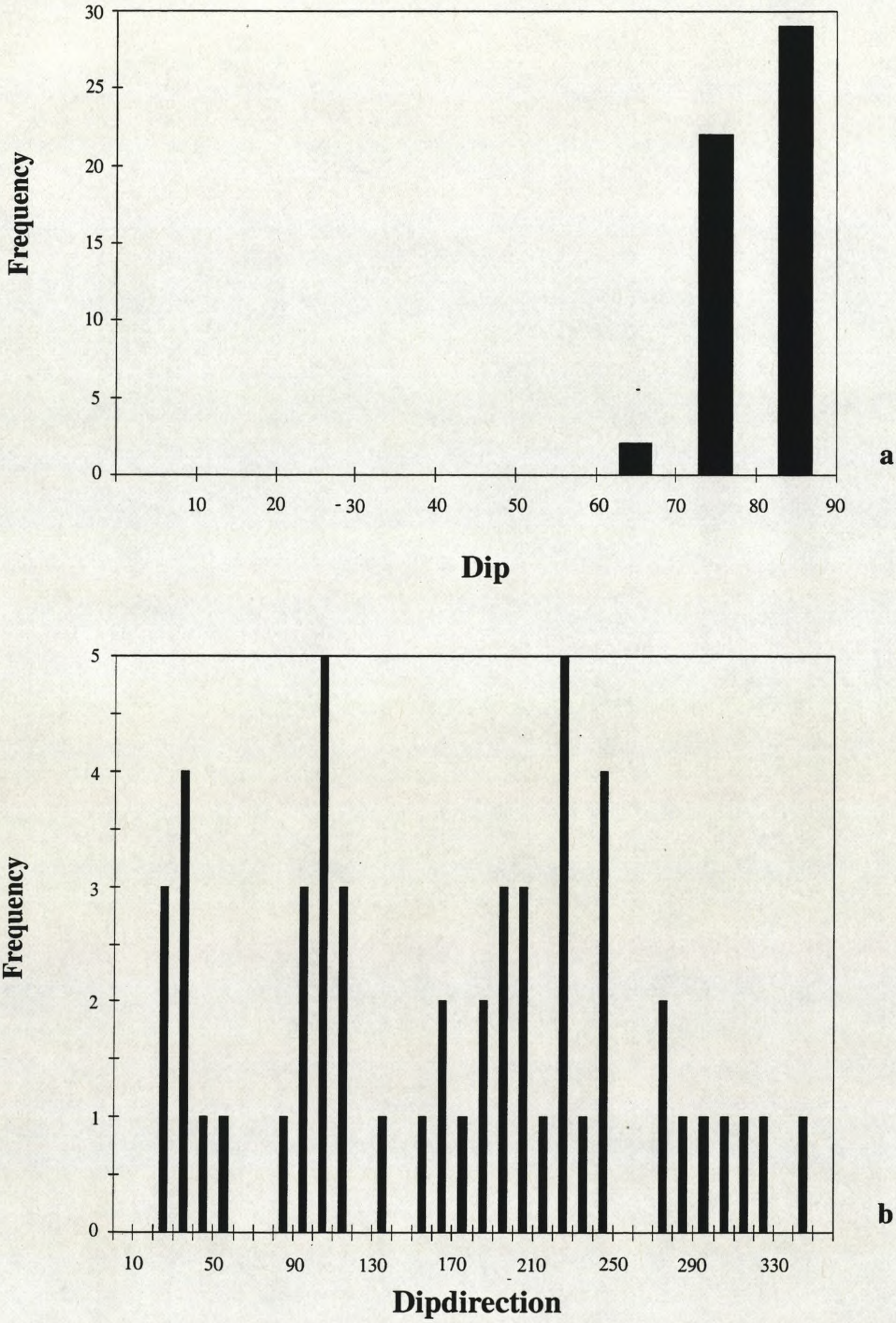
a

Dipdirection



b

Fig. 12



Nye Kløv

Fig. 13

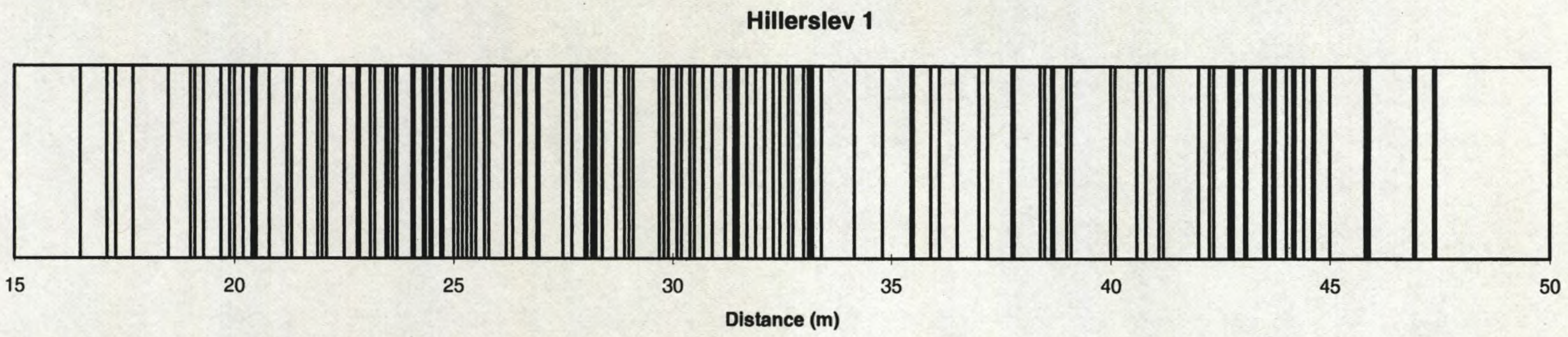


Fig. 14

Hillerslev

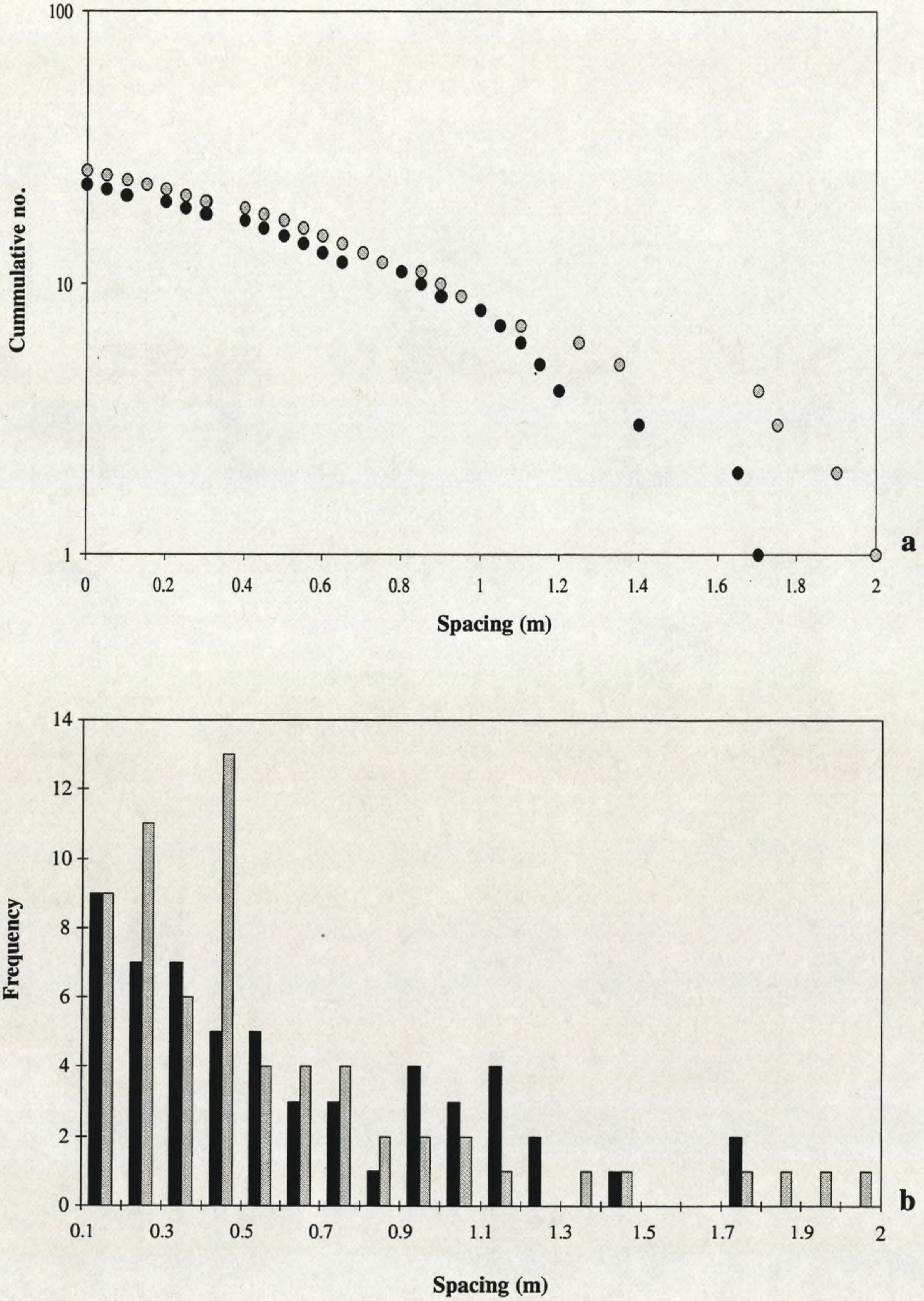


Fig. 15