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MESOZOIC FAULTING IN EAST GREENLAND

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ABSTRACT

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Mesozoic faulting in the East Greenland Basin is interpreted as the result of graben formation extending from a postulated "trilete junction" south of Scoresby Sund. Faults appear slightly curved in plan, but can be divided into straight sections 2 – 10 km long (up to 20° between adjacent segments). They are normal types only, dipping 60° – 80°, with throws up to 4 km – partly resulting from block rotation. Although this rotation implies faults curved in section, they can usually be assumed flat with such large radii of curvature. Major faults are often complex zones (0.5 – 4 km wide) of narrow blocks and slivers. Faulting was partly synsedimentary. Comparisons of pre-Mesozoic and Mesozoic fault directions show fairly similar dominant trends (335°, 355°, 015° – 025°, 035° – 050° & 085° – 090°) in all areas, indicating that pre-existing basement anisotropies controlled directions of Mesozoic-Cenozoic faulting. Basin formation was accomplished by roughly N-S boundary faults in east and west and major NW-SE faults, which together defined a series of fault blocks (subsiding successively from south to north). In Volgian-Valanginian times, the basin was further split into N-S trending antithetic blocks by faults 10 – 30 km apart (crustal extension about 6%).

INTRODUCTION

At the request of Koninklijke/Shell Exploratie en Produktie Laboratorium, Rijswijk, a review was prepared of faulting in the Central East Greenland region. This region is partly occupied by a roughly N-S trending, Mesozoic basin, which appears to have many features in common with the Viking Graben area in the North Sea region.

Exposure in the Central East Greenland Basin area is not ideal, but nevertheless reliable descriptions of fault geometry and valid conclusions regarding fault origins and mechanisms proved possible.

In the last section a possible interpretation of the basin as a failed arm of a trilete junction is outlined, together with implications regarding the sedimentary processes active in the basin.

GEOLOGICAL SETTING

An ice-free zone up to 300 km wide occurs east of the inland ice along the East Greenland coast between 70° and 77°N. The zone becomes narrower from south to north, and the northern part between 75° and 77°N is only 100 km wide. In this zone are exposed from west to east: the ancient Precambrian shield, the late Palaeozoic Caledonian mountain belt and the Mesozoic sedimentary basin.

According to Henriksen & Higgins (1976) the Precambrian terrain has a wider distribution than indicated in the earlier accounts of Haller (1970, 1971), and more and more samples from supposed Caledonian areas give Precambrian ages.

The Caledonian belt mainly comprises highly metamorphosed rocks, especially schists and gneisses. The general structural trend of faults, thrusts and fold axes is NNE. The main Caledonian orogenesis and uplift took place in the Lower Silurian. This event was followed by deposition of up to 7 – 8 km of mainly Devonian molasse. In the Lower Carboniferous a period of folding and faulting took place – this event has been termed the "Final" or "Late Caledonian spasms" (Haller, 1971). The master or bounding faults of

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the Mesozoic basins were initiated during these spasms. In post-Caledonian times a series of fault-controlled basins was formed east of the main border faults, and recent geophysical work indicates that basins with the same structural trend also exist offshore, on the shelf (Johnson *et al.,* 1975).

The Central East Greenland Mesozoic Basin trends in general parallel to the present coastline between 70° – 81°N, and its total onshore length is 800 km with a width of 140 km. It has been argued that the general trend of the coastline was roughly N-S and of the basin NNE; the exposed part of the basin therefore becomes narrower in a northward direction. Actually, the position of the western border faults is shifted eastwards in several steps when going from south to north. Thus the individual subbasins trend parallel to the coastline in a general N-S direction.

The Central East Greenland Mesozoic Basin trends in initiated in early late Palaeozoic times and continued to develop by progressive collapsing until Tertiary times. The fault pattern and its history are the subject of the present report.

MATERIAL USED

The fault patterns described here were extracted from the sources given below.

(1) The 1 : 250 000 geological map of East Greenland between 72° and 76°N by Koch & Haller (1971).

(2) The 1 : 500 000 tectonic map by Haller (1970).

(3) Unpublished 1 : 50 000 maps of the area south of 72°N deposited in GGU (Geological Survey of Greenland).

(4) Preliminary maps at a scale of ca. 1 : 300 000 of the area south of 72°N, published in GGU's report series.

(5) Field observations by the author in the Wollaston Forland area (74° – 75°N).

(6) Study of black and white vertical and oblique aerial photographs throughout the region, and of colour air photographs from northern Wollaston Forland and southern Kuhn Ø.

The maps of Koch & Haller (1971) are generally of high quality, but it must be strongly emphasized that only very few areas have been investigated by more than one or two geologists. The remoteness of the area results also in the geologist's wish to extract all possible information from his observations; extrapolations and binocular geology are therefore practised more often than usual. Mapping normally took place in the early spring, using sledge travel, although the relatively thick snow cover made geological work difficult. Furthermore, at the time of mapping many of the areas were covered only by an, often very poor, old topographic map (1 : 250 000); in some cases more recent vertical or oblique air photographs are now available. The contours on the topographic maps are very much smoothed and give only a rough outline of the topographic features. Thus the position and trend of the faults shown on these geologic maps must be considered to be a sketch rather than the "truth".

Haller's (1970) tectonic map is identical with the geological map with regard to faults and is therefore just as inaccurate.

The more recent maps are not necassarily of higher quality than the old maps, but the airphoto coverage was better and the use of helicopters was more extensive.

EXPOSURE OF FAULTS

Many of the sedimentary areas in East Greenland are very poorly exposed owing to 1) snow cover, 2) solifluction, 3) cover by debris from the Tertiary plateau basalts. The best exposures are found in the Jameson Land area in the south, which is the widest ice-free zone. Unfortunately, this region is practically devoid of faults (except for northern Jameson Land).

On the other hand, the strongly faulted Wollaston Forland region is extremely poorly exposed and only a few gorges display good, more or less vertical exposures. Exposures in plan, which are necessary to show the faults on air photographs, are almost non-existent.

The faults in northern Jameson Land and Scoresby Land (Fig. 1) are well exposed. Furthermore, they are easy to see

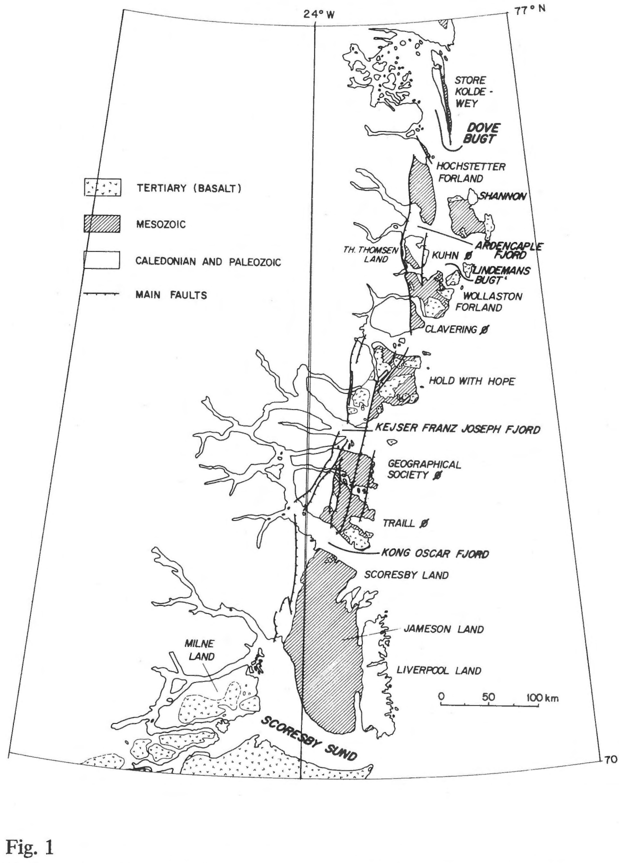


Fig. 1
Map of East Greenland, showing general geology and place names.

in the field, where they cut through variegated Triassic continental deposits. Where they cut through Jurassic sediments, which are more uniform in colour (brownish, greyish), they are more difficult to see. Unfortunately, the faulting of this area is believed to have taken place in Tertiary times, associated with a volcanic period, and the relation between Mesozoic and Cenozoic faulting is uncertain.

On Traill Ø, Geographical Society Ø and Hold with Hope peninsula (Fig. 1) exposures are extremely poor and Tertiary extrusives and intrusives also disturb the picture. The poor exposure is due to the fact that the top sediment beds of both islands consist of soft black Lower Cretaceous mudstones which tend to flow downhill (arctic solifluction) and drape all underlying rocks with a cover of mud.

Furthermore, inspection of vertical aerial photographs, or even oblique air photographs published by the geologists, reveals that several of the faults indicated on the maps are actually large-scale landslides (up to 5 – 6 km wide) and not faults. This is the case for some of the faults postulated by Donovan (1955) on southern Traill Ø, and by Aldinger (1935) on Milne Land. In these regions possibly only satellite images and geological extrapolations and interpretations will be of any help in more detailed fault analyses.

The top sediment beds in Clavering Ø, Wollaston Forland and Kuhn Ø (Fig. 1) mainly consist of mid-Jurassic coarse, well-cemented sandstones, or Late Jurassic – Early Cretaceous, coarse sandstones and conglomerates. Exposure is therefore better than on the islands mentioned above, although not at all of the quality of Jameson Land and Scoresby Land. Triassic or other bright-coloured rocks are almost absent in this region, and the colour differences between two sides of a fault are normally very slight. Furthermore, the formations are thick as compared to the topographic relief and the same formation will therefore often be exposed on both sides of a fault, in spite of an often considerable throw. Faults cutting the conglomeratic units are practically impossible to see in the field or on aerial photographs.

All areas of the investigated region have in common that faults rarely have any topographic expression visible in the field. Only in cases where sediments are down-faulted against Caledonian basement is there a consistently marked topographic expression, but in these cases the fault or fault zone is topographically expressed by a relatively wide valley without exposures. This is, for example, the case along the main border fault in western Wollaston Forland and along the main fault running NNE in eastern Kuhn Ø. A detailed study of the actual fault zone is therefore only very rarely possible.

To sum up, faults are generally only visible in the field when one or more of the conditions below are fulfilled.

(1) Topographic relief is strong, as in northern Jameson Land.

(2) Top sediments are coarse-grained and well-cemented and not soft mudstones. This explains why faults on Traill Ø, Geographical Society Ø and Hold with Hope are extremely poorly exposed.

(3) Faulted sediments are variegated or at least strongly coloured, as in the Triassic rocks of northern Jameson Land and Scoresby Land.

(4) Formations or units with a uniform colour are thin. Unfortunately, in Wollaston Forland most units are more than $\frac{1}{2}$ km thick.

(5) There is no cover by Tertiary plateau basalts and there are no Tertiary intrusives. This explains poor exposures of faults in southern Wollaston Forland, Hold with Hope, Geographical Society Ø and Traill Ø.

(6) There is a strong lithological contrast between the rocks exposed on each side of the faults, in particular where Caledonian basement is faulted against Mesozoic sediments, as on Wollaston Forland and on Kuhn Ø.

Thus in East Greenland the areas best suited for detailed fault analyses in the field are northern Jameson Land – Scoresby Land, where the majority of the faults are believed to be of Tertiary age, and Wollaston Forland – Kuhn Ø.

Because of the open view, without covering forests etc., a helicopter is mainly of help in normal transport only and relatively few extra faults can be observed from the air as compared to those seen in the terrain.

In my experience, study of faults on aerial photographs gives very limited additional information on the areas in question.

NATURE OF MESOZOIC FAULTS

Under this heading some Cenozoic faults are probably included, since it is often difficult to date the faults precisely. Faults can only be safely dated as Mesozoic, if:

(1) they cut Mesozoic sediments which are overlain by younger undisturbed Mesozoic sediments; or

(2) the faults are overlain by unfaulted plateau basalts, as these were extruded in the earliest Tertiary; or

(3) Mesozoic sediments show pronounced facies changes when approaching the faults.

Map view of faults

Curvature – Practically all faults have a curved appearance in plan view (Encl. 1; Fig. 2).

This is a real feature and is not a result of dipping fault planes cutting irregular topography. Only the shorter faults, traceable over a few kilometres, may be completely straight.

The degree of curvature can be expressed by two simple parameters: 1) the maximum length of seemingly straight segments into which one fault can be divided and 2) the variation (in degrees) in strike direction along the fault.

(1) The average length of "straight" fault segments, as can be seen from the enclosed map, varies between 2 km and more than 10 km.

(2) The variation in degrees between adjacent fault segments is up to 20° (Encl. 1; Fig. 2).

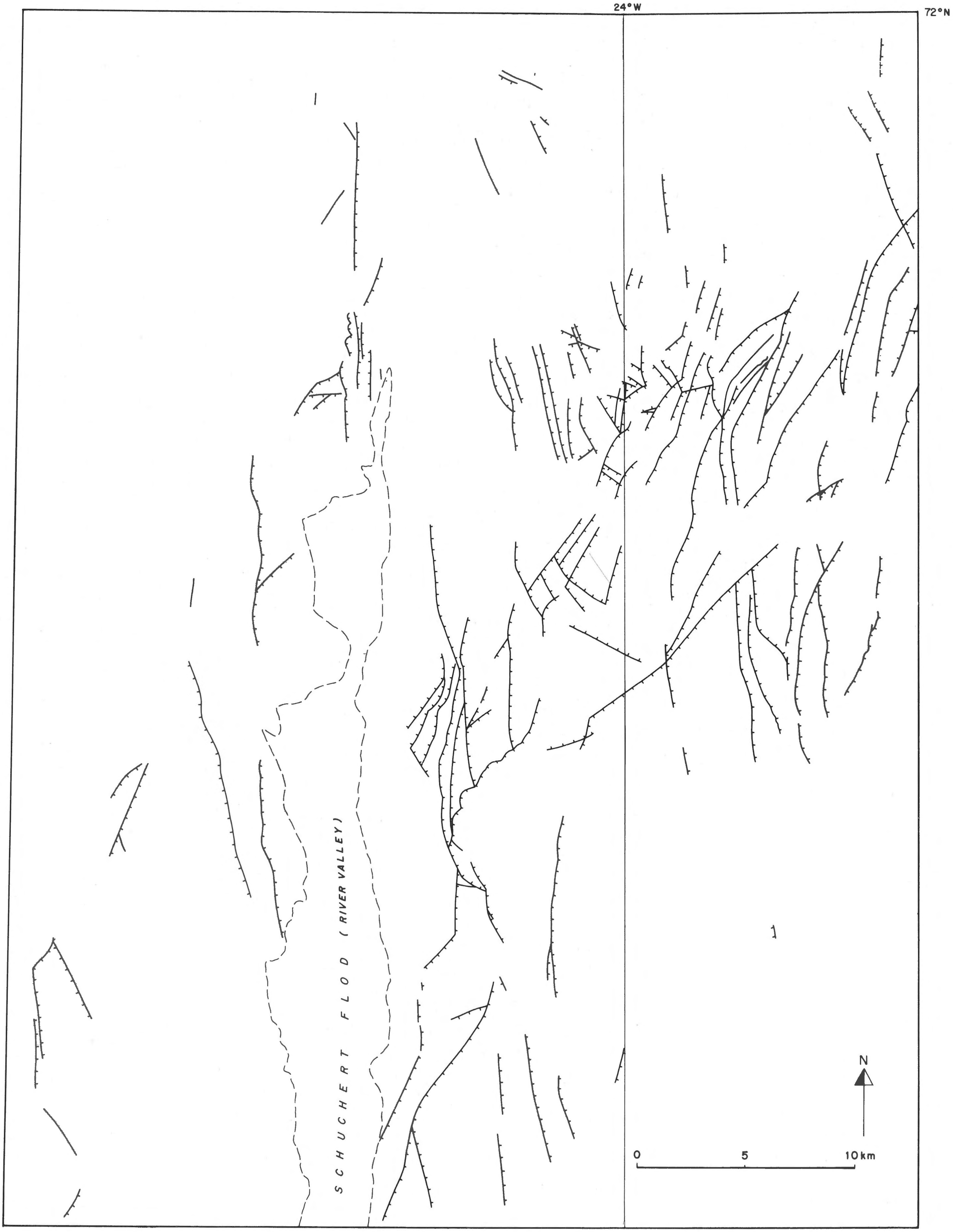


Fig. 2
Mapped faults in the Scoresby Land area (from K. Perch-Nielson, pers. comm., 1977).

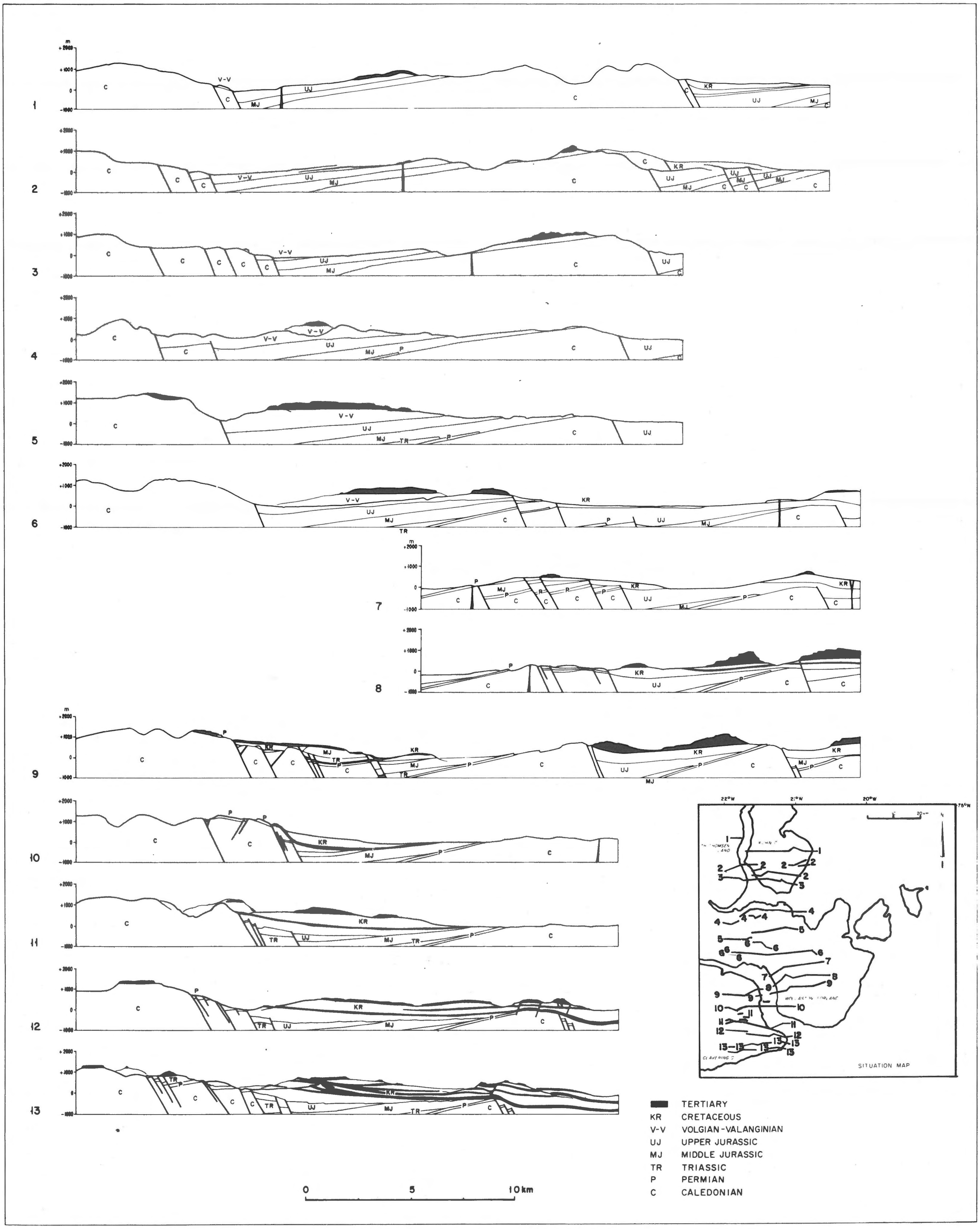


Fig. 3
Cross-sections through the Wollaston Forland area (redrawn from Vischer, 1943).

Although faults are as a rule curved, they rarely make sharp bends. Wherever such a sharp bend is suggested on maps, a closer study may reveal that it is actually another fault crossing, or that the fault splits into two diverging faults (Encl. 1; Fig. 2).

No pronounced systematic pattern in fault curvature can be detected, but there is a tendency towards faults being orientated with their convex side towards the continent and their concave side towards the Atlantic Ocean, or in other words: faults tend to turn to the east when traced in a northward direction (Encl. 1; Fig. 2).

Splitting – Splitting of faults is very common. That it is true splitting can be concluded from the fact that the fault systems are largely synchronous. This, in turn, is based on the observation that in the case of splitting the faults do not intersect, but the "split" takes over part of the original fault's function. The angle of splitting (or anastomosing) normally varies between 15° and 80°.

Vertical sections of faults

Throw – All faults observed are normal faults. Tertiary block faulting and tilting in northern Jameson Land resulted in some localities in down-slope gravity sliding of Triassic strata on older Triassic gypsum layers. The contact plane between the slide unit and an undisturbed unit, in some cases, in the field appears like a reverse fault or a thrust plane. Strike-slip faults have not been observed, but some strike-slip movements in some of the major fault zones following the present-day fjords can be inferred from the general geology on each side of the fjord.

Dip – The dip of the fault planes is only rarely observed. The planes mainly dip in a general eastern direction and the angle of dip seems to vary between 60° and 80°.

Magnitude of throw – The magnitude of down-throw along the normal faults varies from a few metres to several kilometres. The major faults which border the fault blocks normally have a throw of about 1 – 1.5 km. The greatest (inferred) throw is along the western border fault in Wollaston Forland where it amounts to almost 4 km (Fig. 3). The throws on both sides of a fault block may often each attain a magnitude of 2 – 3 km, but it must be stressed that it is the rotation along an axis parallel to the fault trend which is responsible for the vertical displacement, rather than absolute vertical movements.

Curvature of fault planes in vertical sections – No systematic curvature of fault planes can be observed in the field, but can be inferred for the Wollaston Forland area where the fault blocks have been rotated up to 15° – 20° towards the continent. The throw along the fault planes here is of the order of 1 – 2 km and this could not be accomplished without a curved fault plane (concave towards the east). Because of these dimensions I would, however, suggest that the curvature of the fault planes is so gentle (the radius of its containing circle is about 30 km) that it is absolutely impossible to observe it in any normally sized geological section.

For purposes of field geological or oil field work, I therefore propose that the fault planes be treated as flat in a vertical section over a depth of several kilometres. This is an important point, which must be strongly emphasized. The faults are not relatively small-scale growth faults formed in pro-delta sediments by the overload of the prograding delta top, as known from e.g. the Spitzbergen Mesozoic (Edwards, 1976). The East Greenland Mesozoic faults involve several kilometres of Mesozoic sediments and up to at least 5 – 10 km of underlying Caledonian basement. These two fault types have a superficial geometrical resemblance but are on a totally different scale.

Nature of the fault zone

As mentioned above, the faults are rarely simple, but rather constitute a more or less complex fault zone. This zone normally varies in width between 0.5 – 4 km, and is composed of a number of very narrow fault blocks which in general parallel the main fault trend. These blocks may have a width varying from a few hundred metres to ca. 1 km. The cross sections in Figs. 3 & 4 show that movements have only occurred along the down-throwing faults during certain periods and their scarps are very often draped by undisturbed sediments; also, they may show a complex history of repeated movements and drapings.

The upper surfaces of both basement and overlying sediments of the individual blocks in the fault zone are also often strongly eroded and covered with sediments which dip towards the east, i.e. in the opposite direction to the sediments covering the main rotated fault block. It cannot always be ascertained if the dip of these eastwards inclining strata is a primary depositional dip, or if it is due to drag effects along the fault scarp. The two possibilities are illustrated in Fig. 5, with an example from the east coast of Th. Thomsen Land.

Where the sediment cover is thick the nature of the fault zone is often difficult to study, but the existence of underlying narrow blocks or slices of basement east of the main fault is sometimes suggested by monoclinal flexures in the sediment cover (Fig. 3).

Systematic orientation patterns of faults in map view

Even a superficial glance at the tectonic or geologic maps of East Greenland reveals that there is a distinct orientation pattern of faults limiting or cutting the Mesozoic sedimentary rocks. Most authors dealing with the geology of the region have commented upon the fault trends, but oddly enough no systematic study of the faults has yet been under-

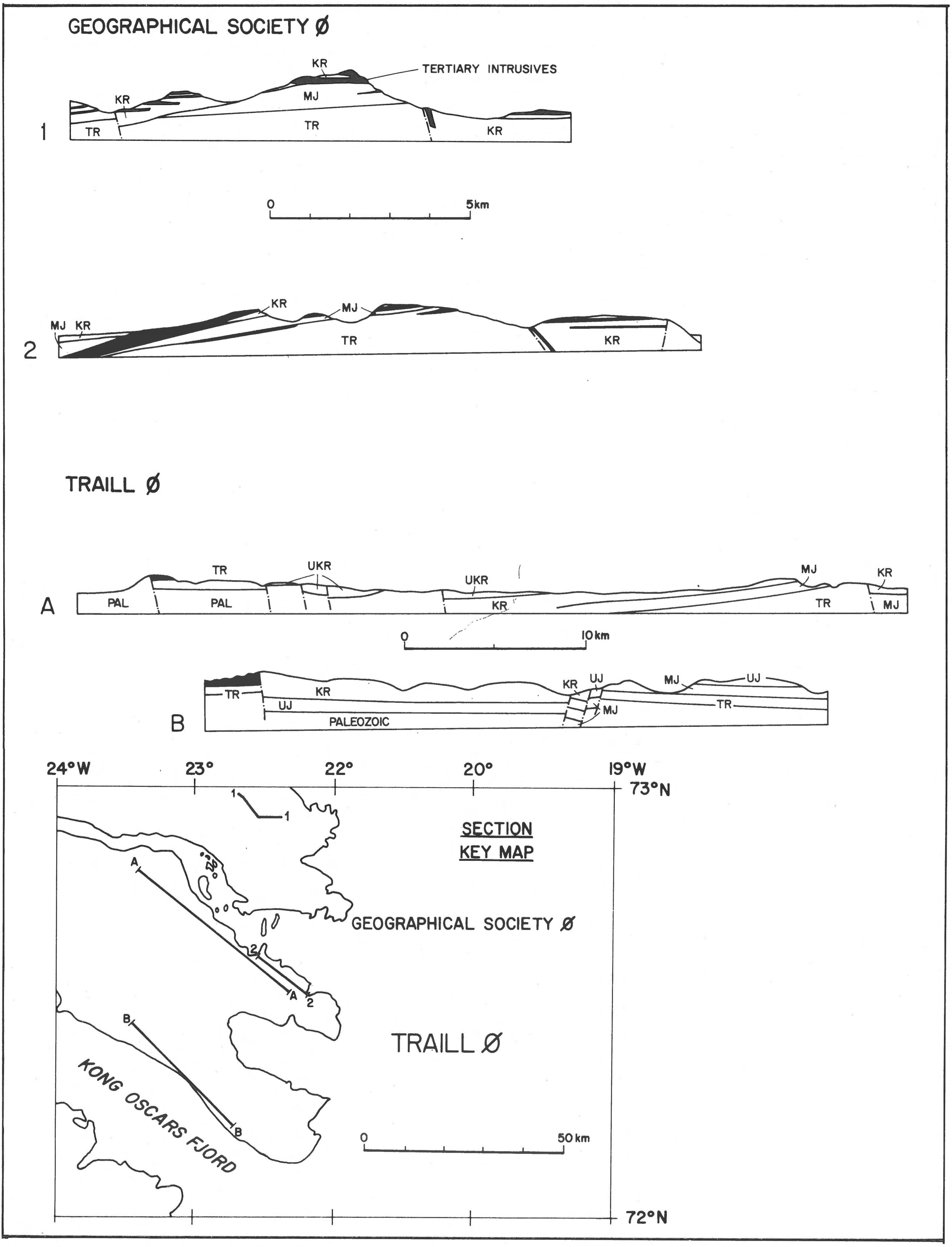
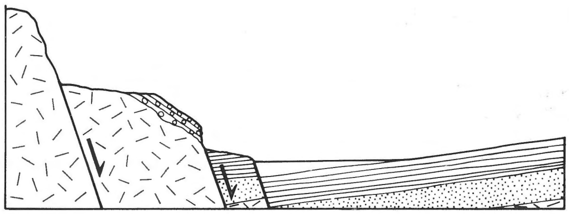
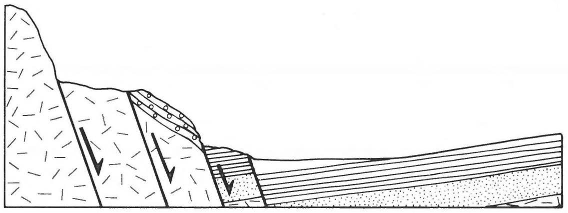


Fig. 4
Cross-sections through Traill Ø and Geographical Society Ø (redrawn from Donovan, 1953; 1955).



a.- DEPOSITIONAL TILT



b.-DRAG EFFECT

Fig. 5
Strongly eastwards tilted Mesozoic sediments in major fault zone, showing two possible interpretations, a & b; the latter is preferred in the present case.

taken. Most authors restrict themselves to statements on the general fault trends. Thus it is generally agreed that in the Mesozoic two fault systems were active: one striking NNE and claimed to parallel the main Caledonian lineaments, and one striking NNW (Vischer, 1943; Haller, 1970).

To give a somewhat more objective and quantitative idea of the fault trends and the relative importance of the different trends, data on fault lengths and orientations have been compiled in Fig. 6. The data were collected from all available maps (mentioned in the section on "Material used"). The main sources are Haller's (1970) tectonic map (1 : 500 000) and unpublished GGU maps (1 : 50 000) from Jameson Land and Scoresby Land.

The following categories of lineaments are distinguished by Haller (1970) and these names are also used here.

(1) Old Caledonian lineaments. These are results of the Main Caledonian orogeny of Silurian age.
(2) Young Caledonian lineaments. These correspond to the so-called Late Caledonian Spasms and are of Devonian age.
(3) Carolinidean lineaments. Correspond to a little-known Middle Proterozoic orogenic complex located between 76° and 81°N.
(4) Upper Palaeozoic lineaments.
(5) Palaeozoic to Cenozoic lineaments.
(6) Mesozoic to Cenozoic lineaments.

In the Caledonian terrain only lineaments such as fold axes are measured, whereas faults are neglected. This is a necessary procedure, since many of the faults which only cut Caledonian rocks are, with little doubt, of Mesozoic – Cenozoic age. If this procedure was not followed, one would, in studying the influence of basement tectonic grain on the Mesozoic faulting, easily find oneself testing Mesozoic orientations in the basement area against Mesozoic orientations in the neighbouring Mesozoic area. This pitfall is avoided by the procedure described above.

The six categories of lineaments reflect the local geology in the different regions. Where Palaeozoic rocks are absent, categories 4 and 5 thus fall out.

The measurements were made in the following way. Each lineament is measured for length and orientation. Then all measurements in each category are summed up, divided into 10° classes and finally plotted in histograms as percentages. Much subjectivity is introduced in the choice of which lineaments should be excluded, etc. This is especially the case for faults extrapolated across wide fjords. Plotting in histograms is slightly awkward for circular distributions, but is preferred here to plotting in rose-diagrams, because the latter are very difficult to compare visually.

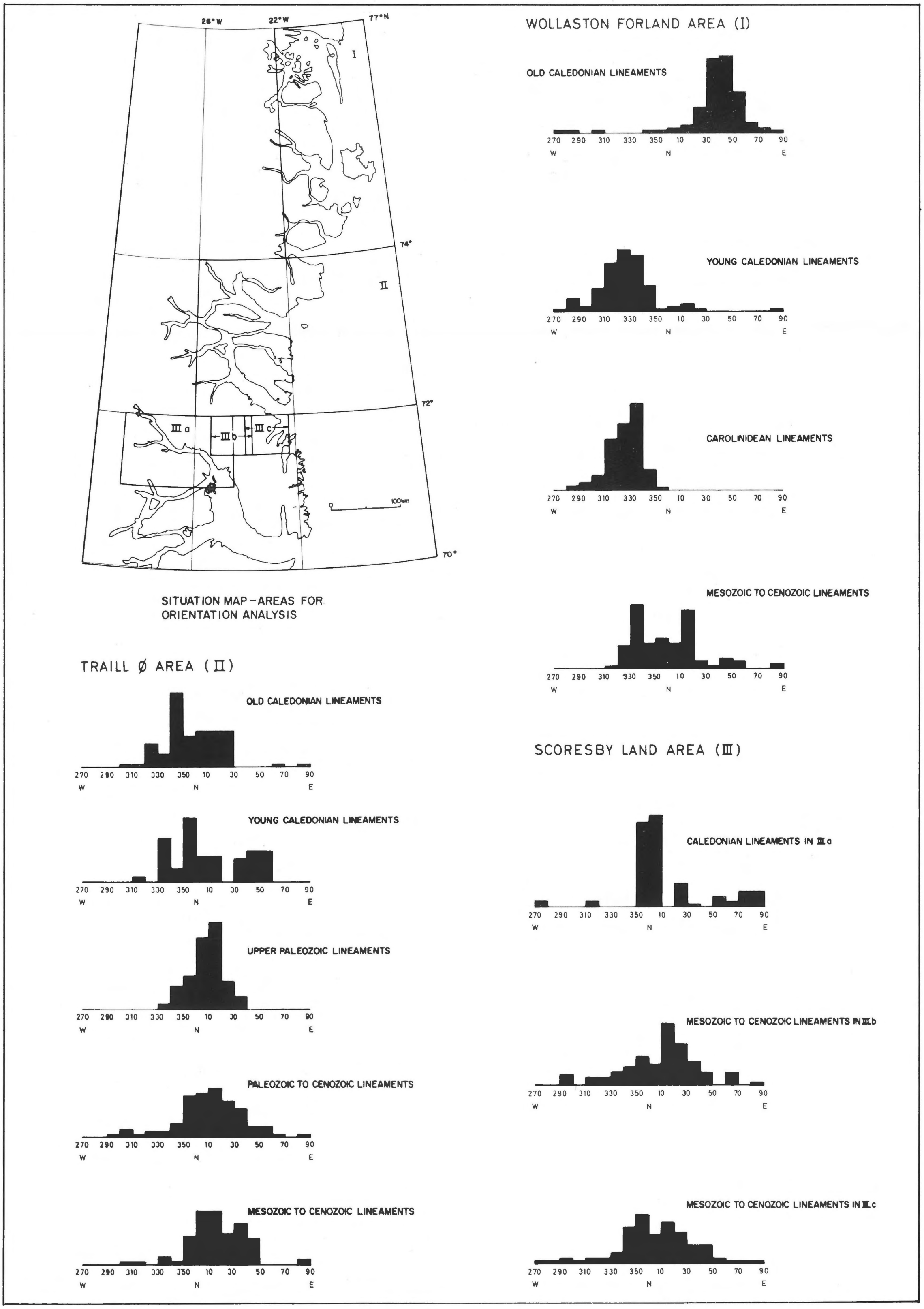
The area investigated is divided into three areas in the orientation analysis (Fig. 6):

Wollaston Forland area (I),
Traill Ø area (II),
Scoresby Land area (III).

These areas will now be considered in turn.

I. *The Wollaston Forland area* –
(1) The Old Caledonian lineaments show a strong trend between 30° and 60° with a mean around 40° (NE).
(2) The Young Caledonian lineaments show a pronounced trend between 310° and 340° with a mean around 325° (NW – NNW). Two small secondary peaks can be seen with means around 15° (NNE) and 285° (WNW).
(3) The Carolinidean lineaments are also pronouncedly unimodal, varying between 310° and 340° with a mean around 325° (NW – NNW).
(4) The Mesozoic lineaments are strongly bimodal with three subordinate peaks. The two major peaks vary between 320° and 350° with a mean around 335° (NNW), and between 0° and 30° with a mean around 15° (NNE). A third peak with a mean around 355° (N) can probably be recognised between the two strong peaks, and two small extra peaks occur with means around 50° (NE) and 85° (E).

A comparison of the four histograms shows a pronounced correlation between the Young Caledonian and Carolinidean 325° (NW – NNW) means. This strong mean correlates well with the Mesozoic 335° (NNW) mean. The other prominent Mesozoic mean, 15° (NNE), correlates with the small Young Caledonian 15° (NNE) mean, but the relations are not so clear in this case.



ig. 6
istograms showing orientation of lineaments from three subareas.

The Mesozoic 355° (N) peak does not seem to have a counterpart in any of the older lineaments.

The Old Caledonian 30° – 60° (NE) peak corresponds well with the small 40° – 60° (NE) Mesozoic peak.

Finally, the small 85° (E) Mesozoic lineament might correlate with both Old and Young Caledonian E lineaments.

In conclusion it can be stated that, in the Wollaston Forland area, the correlation between the Young Caledonian and Carolinidean NW – NNW trend with the Mesozoic NNW trend is so strong that, with little doubt, Mesozoic faulting followed the older structural lines. The Mesozoic N peak is seemingly a new feature unrelated to earlier trends. The Mesozoic NNE trend correlates with a subordinate but well defined Young Caledonian NNE trend and is thought to be directly dependent on this trend. Finally, the Mesozoic E trend might correlate with an indistinct Young Caledonian E trend.

II *The Traill Ø area –*

(1) The Old Caledonian lineaments show a small distinct peak with a mean around 325° (NW – NNW). The most prominent peak has a mean around 345° (NNW), and finally there is a broad diffuse peak between 0° and 30° with a mean around 15° (NNE).

(2) The Young Caledonian lineaments show three well-defined peaks. One with a mean around 335° (NNW), one with a mean around 355° (N), and one varying between 30° and 60° with a mean around 45° (NE).

(3) The upper Palaeozoic lineaments show a very broad, but well-defined peak. It varies between 330° and 40° with a mean around 10° (N – NNE).

(4) The Palaeozoic to Cenozoic lineaments show an even broader peak between 320° and 70° with a mean around 10° (N – NNE). Another much smaller peak has a mean around 305° (WNW).

(5) The Mesozoic to Cenozoic lineaments show a not too well-defined bimodal distribution with one mean around 10° (N – NNE) and another around 35° (NE – NNE). Two very small peaks have means around 85° (E) and 335° (NNW).

In conclusion, it can be stated that the Old and Young Caledonian histograms are markedly similar, although the Young Caledonian NE orientation does not have an Old Caledonian counterpart.

Likewise, the three post-Caledonian histograms are also very similar although the Mesozoic 35° mean (NE – NNE) is weakly or not at all represented in the other two histograms. This 35° peak may, however, correlate with the Young Caledonian NE peak between 30° and 60°. The main post-Caledonian trend is the very strong 10° (N – NNE) direction. It seems to correlate with the rather poorly defined, but important Old Caledonian peak between 0° and 30° (NNE).

The orientation of the Mesozoic lineaments was thus, without much doubt, determined by both Old and Young Caledonian structures, and no new directions seem to have been formed.

III. *The Scoresby Land area –*

(1) The Caledonian lineaments show a strong peak between 350° and 10° with a mean around 0° (N). Smaller peaks occur around 25° (NNE), 55° (NE – NNE), and 80° (E), but the Caledonian data from this region are sparse and a few additional lineaments might alter the pattern significantly.

(2) The Mesozoic to Cenozoic lineaments in area III.b show two strong peaks with means around 355° (N) and 20° (NNE).

(3) The Mesozoic to Cenozoic lineaments in area III.c also have a bimodal distribution with peaks around 355° (N) and 20° (NNE).

When the remarks about the relatively few data on Caledonian lineaments are taken into consideration, the correlations between the Caledonian and the Mesozoic trends are remarkably good. The two main Mesozoic trends 355° (N) and 20° (NNE) both seem to be controlled by older, Caledonian structures.

Conclusions – When the results from the three areas investigated (I, II, III) are compared, the points below emerge.

(1) The main Mesozoic trends are very well defined but change from area to area.

(2) A NNW (335°) trend is well developed in areas I and II. The trend is basement-controlled in both areas.

(3) An almost N-S trend (355°) occurs in both areas I and III, but basement control can only be demonstrated in area III, where it is a major trend.

(4) A NNE trend exists in all three areas but shifts from 15° in area I, to 10° in area II to 25° in area III. This trend is basement-controlled in all three areas.

(5) A NE trend can be demonstrated in areas I and II (50° and 35° respectively) and is also controlled by the Caledonian basement grain.

(6) Finally, a minor E trend (85° – 90°) can be recognised in all areas, although it is relatively indistinct in area III. Again, this trend appears to correspond to a well defined basement trend.

In this connection it should be mentioned that much discussion about the influence of basement anisotropy on Mesozoic faulting has been focussed on the northern North Sea – an area where, for physical reasons, it is almost impossible to demonstrate any relationships between the basement and the Mesozoic structures. One of the very few areas in the North Sea – North Atlantic region where such a relationship can be studied and tested is East Greenland. In the author's opinion the above results support beyond doubt the hypothesis that, although the Mesozoic faulting in itself is unrelated to Caledonian basement structures, the actual orientation of the Mesozoic faults is strongly dependent on the basement anisotropy.

TIMING OF FAULTING

The dating of faulting in a tectonically relatively undisturbed area like the East Greenland Mesozoic Basin is very difficult. Several different lines of evidence, listed below, were employed in the present study.

(1) Faults may cut a sequence which is unconformably overlain by an unfaulted sequence. The overlying sequence may be completely undisturbed or may show a gentle monoclinal flexure over the fault. This is due either to primary topography across the fault or to later weak movements on the fault.

(2) Rapid lateral changes to coarser facies when approaching a fault suggest that the fault was active at the time of deposition or at least shortly before deposition.

(3) Abrupt disappearance of thick litho- or biostratigraphic units when crossing a fault.

Whereas the features of the first two approaches (1 & 2) are relatively simple and can be observed in the field, the last approach (3) requires, often very detailed, biostratigraphic work, or at least that mapping on both sides of a major fault zone (which often follows the large fjords) is done by the same geologist. Sykes & Surlyk (1976), for example, demonstrated that the lower half of the dark shaly Upper Oxfordian – Kimmeridgian Bernbjerg Formation as known from Wollaston Forland disappears abruptly when crossing the fjord north of Wollaston Forland to Kuhn Ø. This was interpreted as a Kimmeridgian basin extension by down-faulting of the northern block. Such studies cannot be undertaken in the field and require detailed knowledge of (and presence of) zonal ammonites.

Studies along the above lines have clearly demonstrated a number of relatively well defined Mesozoic episodes of faulting (Surlyk, in press).

In the Triassic the evidence of faulting is mainly indirect from facies studies. In middle Triassic times thick alluvial fan sequences were formed along both the western and eastern margins of the Jameson Land Basin. Transport was away from the faults towards the basin centre, and the alluvial fans are thought to have formed fringes along the scarps of the bordering fault zones.

From Early Jurassic times the evidence becomes more precise. Whereas the Middle-Upper Triassic sediments are very difficult to date and correlate, because they show very rapid lateral facies changes and contain almost no age-diagnostic fossils, the Jurassic rocks are all marine, contain ammonites, and are laterally very persistent.

In Rhaetic times the Jameson Land Basin was down-faulted along a major fault zone following Kong Oscars Fjord, and Traill Ø stood up as high land. Both Rhaetic and Liassic sediments are absent north of the fjord, whereas they are very uniformly distributed in Jameson Land, where they reach a relatively constant thickness of about ½ km (Surlyk *et al.,* 1973).

Mid-Jurassic rocks, on the contrary, spread uniformly over both Jameson Land and Traill Ø. The Traill Ø block was thus down-faulted along the Kong Oscars Fjord Fault to the same level as the Jameson Land block at the Lower/Middle Jurassic boundary. General basin subsidence seems to have taken place continuously by slow movements along the main N-S border faults.

Mid-Jurassic fault-controlled subsidence can also be demonstrated in the Wollaston Forland area (Surlyk, in press).

In the Upper Jurassic, several episodes of fault-controlled subsidence have been demonstrated by Sykes & Surlyk (1976) and Surlyk (in press). Thus regional "stepwise" fault-controlled deepenings of the basin can be dated as Early Oxfordian, Late Oxfordian and Early Kimmeridgian.

None of the Jurassic (or Triassic) fault episodes seem to have broken up the initial wide N-S orientated fault blocks into narrower blocks. The main fault-controlled subsidence was accomplished by movements along the main western (and eastern) border faults, and by movements of a more "stepwise" nature along a system of fault zones following the present-day fjords: Kong Oscars Fjord, Kejser Franz Josephs Fjord, "Lindemans Bugt" and Ardencaple Fjord. All the latter fault zones are orientated NW-SE and they do not appear clearly in the histograms, because they are not exposed. Their existence has, however, been proved beyond doubt. All of the faulting described above was normal faulting which was not accompanied by any clear antithetic block rotation.

The most important Mesozoic tectonic phase was the very strong antithetic block faulting which took place at the Jurassic/Cretaceous boundary (Volgian – Valanginian). This phase, which in much oil-geology literature is referred to as the "Late Cimmerian Phase", can be traced all over the northern North Sea – North Atlantic area. In East Greenland it was first described by Vischer (1943) and Maync (1947, 1949) and comparisons of its effects in different areas were made by Surlyk (1975).

In the Wollaston Forland area the Mesozoic platform underwent its first major period of collapse in this Volgian – Valanginian phase. The initially up to 100 km wide fault blocks were broken up along mainly NNW, N, and NNE trending lines into a series of narrow (10 – 30 km wide) blocks with bordering fault zones split up into a number of very narrow blocks or slices. The blocks were strongly rotated towards the continent (W) simultaneously with faulting, and the maximum westward tilt of the surface of individual blocks when the tectonic phase faded out, in the Valanginian, was as much as 15°. The total throw along fault planes was of the order of 1 – 4 km, but again it must be mentioned that the rotation is responsible for the vertical displacement of the blocks rather than absolute regional vertical movements. The faulting and rotation were not continuous but seem to have occurred in about 3 to 5 major episodes. This can be seen from intraformational angular unconformities and facies distribution. During each major phase the initial blocks were further fragmented (Fig. 7).

The antithetic nature of the faulting was interpreted by

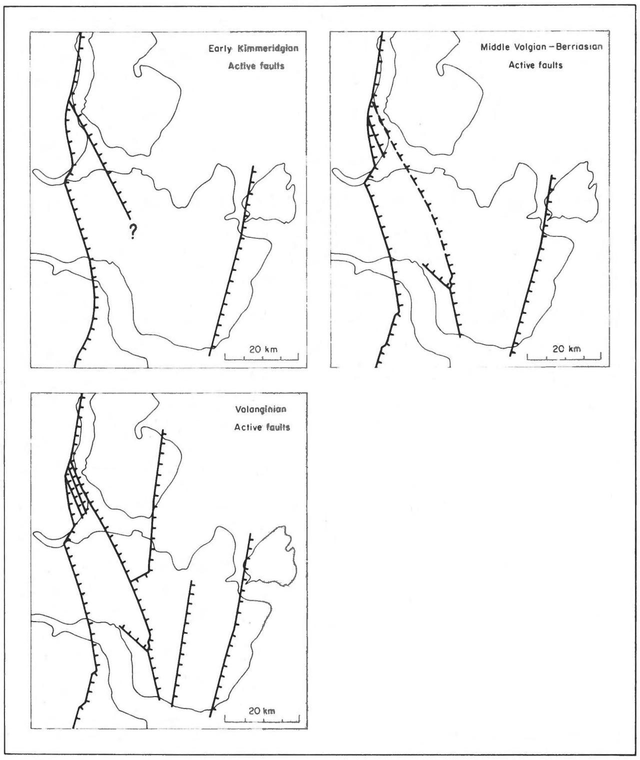


Fig. 7
Timing of faulting in the Wollaston Forland area.

Vischer (1943) as due to crustal extension, and he estimated the total extension over the 50 km broad coastal strip at ca. 3 km, i.e. 6%.

From a study of the faults which involve many kilometres of both cover and basement, and of the sedimentary fill of the fault-bounded troughs, it is clear that the crustal extension and the resulting antithetic block faulting is the primary feature, and that the sediment filled the tectonically-formed troughs as a secondary response. The load of sediment after the first period of faulting of course helped in sustaining the basin's subsidence. The structures are thus fundamentally different from "growth faults" where the sediment load is the driving mechanism in faulting.

Figure 8 shows a photomosaic of a block crest area in southwest Wollaston Forland seen from the north. To the right (west) is the down-dip direction of the block, whereas the block crest is to the left (east). The lowest exposed sediments are of middle to Late Jurassic age. They are strongly tilted westwards and cut by several faults of the Volgian – Valanginian phase. To the west they are overlain unconformably by syntectonic Valanginian conglomerates. The conglomerates thin very rapidly to the east, and on the block crest the syntectonic classic wedge is represented only by a thin condensed marine Valanginian red bed. Analogous Mesozoic red beds are well known from other structural highs in the northern North Sea and North Atlantic Ocean e.g. on Andøy, northern Norway (Dalland, 1975). The sequence is finally overlain, above an erosional and angular unconformity, by Lower Cretaceous mudstones. The whole setting is a perfect cross-section of a northern North Sea oil field. Middle Jurassic sandstones (reservoir rocks) overlain by black Upper Jurassic shales (source rocks) are faulted, tilted and unconformably overlain by more or less horizontal mudstones of Early Cretaceous age (seal).

To the south in the Jameson Land Basin the Volgian – Valanginian tectonic phase can only be indirectly observed and no antithetic block rotation can be demonstrated. The tectonic activity is mirrored by a facies shift from fine-grained shales to very rapidly deposited thick formations mainly composed of coarse pebbly sandstones. The formations contain several minor angular unconformities (Surlyk, 1973; Sykes & Brand, 1976).

On Traill Ø and Geographical Society Ø westwards-tilted Middle to Late Jurassic sediments (as in Wollaston Forland) are unconformably overlain by Lower Cretaceous mudstones, but both structure and stratigraphy are less clear than in Wollaston Forland (Donovan, 1953, 1955).

The Cretaceous is not so well known as the Jurassic, partly because Cretaceous sediments are restricted to smaller outliers and rarely form continuous outcrop belts.

However, on the basis of observed unconformities, fault activity has been postulated to have taken place in the Aptian, Albian, and Turonian (Maync, 1949; Donovan, 1957).

LATERAL WEST-EAST SHIFTING OF FAULT ACTIVITY

Following Vischer (1943), many authors have proposed that the locus of faulting shifted successively eastwards during Mesozoic times.

On a broader scale it is true that the whole post-Caledonian history of faulting and basin formation seems to give a picture of eastward shifting of the major fault activity. Thus two major lineaments in particular reveal the eastward shift, namely the so-called "Kong Wilhelm's Line", which can be traced from 74° to 77°N, paralleled some 70 km to the east by the "post-Devonian Main Fault", which runs from 70° to 77°N. The first was the site of considerable activity and repeated displacement from Lower to early Upper Devonian times. The "post-Devonian Main Fault" came into being in the Carboniferous and remained active throughout Mesozoic and Cenozoic times.

In contrast to all earlier authors, however, I do not agree on the eastward shifting of tectonic activity in Mesozoic times. The western borders of all basins and subbasins seem to have been relatively constant, and by far the thickest successions from all periods are found along the western border faults. Therefore, I prefer the interpretation that the Mesozoic platform disintegrated and partially collapsed in a series of fault episodes of which the Volgian – Valanginian was

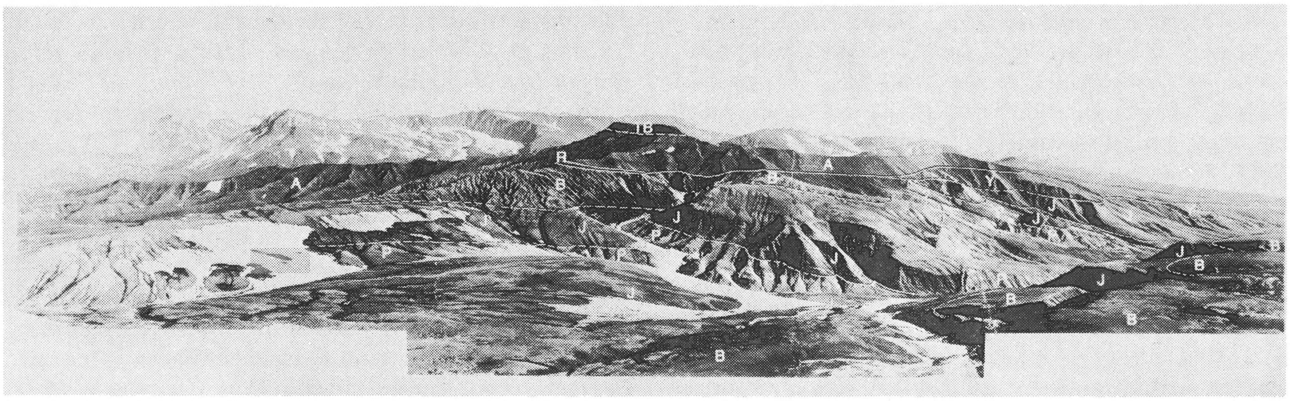


Fig. 8
Photomosaic of southern side of Cardiocerasdal, southwest Wollaston Forland. P = Pelion Member (Middle Jurassic); J = Jakobsstigen Member (Early Upper Jurassic); B = Bernbjerg Formation (Upper Jurassic); Y = Young Sund Member (Valanginian, Lower Cretaceous); R = Rødryggen Member (Valanginian); A = Aptian-Albian; TB = Tertiary basalts.

by far the most important. There is not the slightest sign of the western blocks being progressively structurally dead throughout the Mesozoic.

JURASSIC "FAILED-ARM" SEDIMENTATION IN EAST GREENLAND

During work over the past six months on Jurassic fault-tectonics and sedimentation in East Greenland, a completely new picture of the basin formation emerged. All ideas of sediment transport and environments within the basin had to be modified and worked into this general model.

The present review was originally intended only to deal with fault tectonics and geometry; sedimentary facies and stratigraphy have been omitted. However, it is the author's opinion that the new model for basin formation is tectonically relevant and has considerable bearing on the geological history of the northern North Sea oil fields and, on a more detailed level, on the prediction and extrapolation of sand body geometry. The paper will therefore be concluded with a brief discussion of this model.

As described in the preceding sections the Mesozoic basin of East Greenland is orientated more or less N-S, almost parallel to the coast. It is also parallel to those parts of the North Atlantic spreading axes which are situated east of the Central East Greenland coast.

Several Mesozoic phases of faulting and rifting can be recognized, and it has been proposed that the Jurassic/Cretaceous boundary phase of rifting could be considered the initial phase of rifting preceding the actual spreading (Hallam, 1971).

Several authors have proposed the existence of one or more trilete junctions in East Greenland, and since spreading is known to have taken place along a N-S axis, the existence of a "failed arm" has been proposed to run at an angle to the coast. Thus Brooks (1973) suggested a non-spreading rift running inland from the Kangerdlugssuaq volcanic area at almost right angles to the coast and others have proposed that a trilete junction occupied the position of the mouth of the Scoresby Sund Fjord area and that the W-E orientated fjord was the site of a "failed arm".

There is, however, absolutely no field evidence for any of these proposed "failed arms" and the reason is probably that these arms have always been sought at right angles to the coast, because the final spreading axis runs parallel to the coast.

The onset of Jurassic basin formation, however, took place 145 million years before the actual drift began in early Tertiary times, and the most important episode of Mesozoic rifting took place 80 million years before drift. The 80 million years correspond to the tectonically relatively quiet Cretaceous period.

If the Mesozoic basin is investigated by itself, and the much younger Cenozoic spreading initiation not taken into consideration, a very interesting pattern emerges for the Jurassic sedimentation. After the Triassic period of mainly continental sedimentation in fault-controlled N-S orientated intermontane basins, the Jurassic sea was established by progressive down-faulting, accompanied by a general eustatic rise of sea level. The initial faulting followed the Caledonian structural trends as demonstrated above, and a N-S elongated sea was formed which to the west was limited by a major en echelon fault zone. The first marine basin of Liassic age covered the Jameson Land – Scoresby Land area; it was bordered to the east by the Liverpool Land structural high and to the north by the Traill Ø block, which was relatively uplifted along the Kong Oscars Fjord fault zone. Subsidence was uniform throughout the area and was probably accomplished by movements along the main border faults.

In early mid-Jurassic times the basin was extended northwards by down-faulting of the Traill Ø – Geographical Society Ø block, and through the Middle and Upper Jurassic this block formed one structural unit with the Jameson Land block. Subsidence was again rather uniform, but greatest in northern Jameson Land and on Traill Ø, once more mainly accomplished by movements along the main border faults, probably overprinted with a general Late Jurassic eustatic rise in sea level.

In the Hold with Hope area north of Geographical Society Ø, rocks of Jurassic age are absent. Some authors have argued that the absence is primary and that Hold with Hope formed a landmass in the Jurassic (e.g. Maync, 1947, 1949), whereas others have suggested the absence to be secondary, due to upheaval and erosion of the area in Early Cretaceous, pre-Aptian times (Donovan, 1957).

Kejser Franz Josephs Fjord separates Hold with Hope from Geographical Society Ø and might, like most of the other East Greenland fjords, conceal a major fault zone. As supporting evidence, it can be mentioned that one of the most important tectonic lineaments in the Greenland Sea is the Jan Mayen Fracture Zone. This zone terminates exactly at the mouth of Kejser Franz Josephs Fjord (Johnson *et al.,* 1975) and, although it belongs to the spreading system, it seems reasonable to suggest that it is also of some palaeogeographic significance in the Jurassic. Hold with Hope is thus interpreted as a fault block bounded in N-S direction by the main Mesozoic fault zones and to the south by the Kejser Franz Josephs Fjord fault zone. The Mesozoic basin was then first extended to Hold with Hope by down-faulting in Cretaceous (Aptian) times.

The western border fault of the Mesozoic basin is the same for the whole area from Jameson Land to Hold with Hope. North of Hold with Hope it jumps en echelon to the east where it runs from southeastern Clavering Ø over Wollaston Forland and Th. Thomsen Land to northern Hochstetter Forland. The Jurassic sea first spread over this region in mid-Jurassic times. At first it covered only the Clavering Ø – Wollaston Forland block which was down-faulted with respect to the Kuhn Ø block to the north along a NW-SE fault zone in the fjord south of Kuhn Ø. Subsidence was uniform throughout the basin and was accomplished by movements on the N-S border faults. In late mid-Jurassic times the Kuhn Ø block was down-faulted to the same level as the Clavering Ø – Wollaston Forland block, and until early or late Oxfordian times the two blocks acted as one structural unit on which subsidence was uniform and again accomplished by movements along the main border fault. In the latest mid-Jurassic or in early Late Jurassic times the Hochstetter Forland block started submerging. Until then it was uplifted with respect to Kuhn Ø and formed a landmass limited to the south by a NW-SE trending fault zone following the outer part of Ardencaple Fjord.

After this last northward basin extension by progressive down-faulting, the Hochstetter Forland block seems to have acted more or less as part of the same structural unit as the Clavering Ø – Wollaston Forland – Kuhn Ø block since Early or Late Oxfordian times.

The Wollaston Forland block then underwent further down-faulting in the early and late Oxfordian and in the Kimmeridgian. The basin extension to the north became, however, well established through Oxfordian to Kimmeridgian times. The Middle to Upper Jurassic sections became progressively thinner and more fragmentary from Wollaston Forland to Kuhn Ø to Hochstetter Forland.

North of Hochstetter Forland the Mesozoic border fault and the coastline again seem to jump en echelon to the east. The fault zone is situated either in Dove Bugt west of Store Koldewey, or it is represented by the N-S fault that divides Store Koldewey longitudinally. The western side is composed of Caledonian basement and the eastern part comprises mid-Jurassic to Valanginian sediments. The mid-Jurassic rocks seem to rest directly on the basement and represent the first transgression of the area. The later Jurassic history is too fragmentary to add anything of tectonic importance.

The exposed part of the Jurassic basin of East Greenland is thus very broad in the south (140 km) and becomes narrower in a northward direction (10 – 20 km). This narrowing is not a result of the faults running at an oblique angle to the coast. The individual blocks become narrower to the north, and the western border faults are in at least three places shifted 10 – 30 km eastwards by cross faulting or by en echelon take over. The eastern border faults are more N or even NNW orientated than the generally NNE orientated western faults.

The outline of the basin thus has the shape of a N-S elongated triangle or wedge (Fig. 9). The formation of the basin was initiated to the south and its structural evolution can thus be described as a stepwise northward basin extension by progressive down-faulting along NW-SE trending faults accompanied by a general subsidence accomplished along N-S trending faults.

The sedimentary facies are correspondingly of progressively more proximal nature in a northward direction within each "en echelon block", as well as going from block to block.

The transport pattern of all sandstone bodies of Middle to Late Jurassic age is extremely uniform, except those resulting from the Volgian – Valanginian antithetic block faulting. The depositing currents flowed persistently in southerly directions in all subbasins, and the depositional environments for the sand bodies seem to have been roughly uniform in nature; fluvio-marine estuarine deltas coming from the north, landlocked between fault scarps to the west (and north) and block crests to the east. The extremely uniform transport pattern can be seen in the Bathonian – Callovian (and to the north, Bathonian – Oxfordian) Pelion Member in Jameson Land, Scoresby Land and Trail Ø, Wollaston Forland, Kuhn Ø and Hochstetter Forland (Surlyk *et al.*, 1973; Sur-

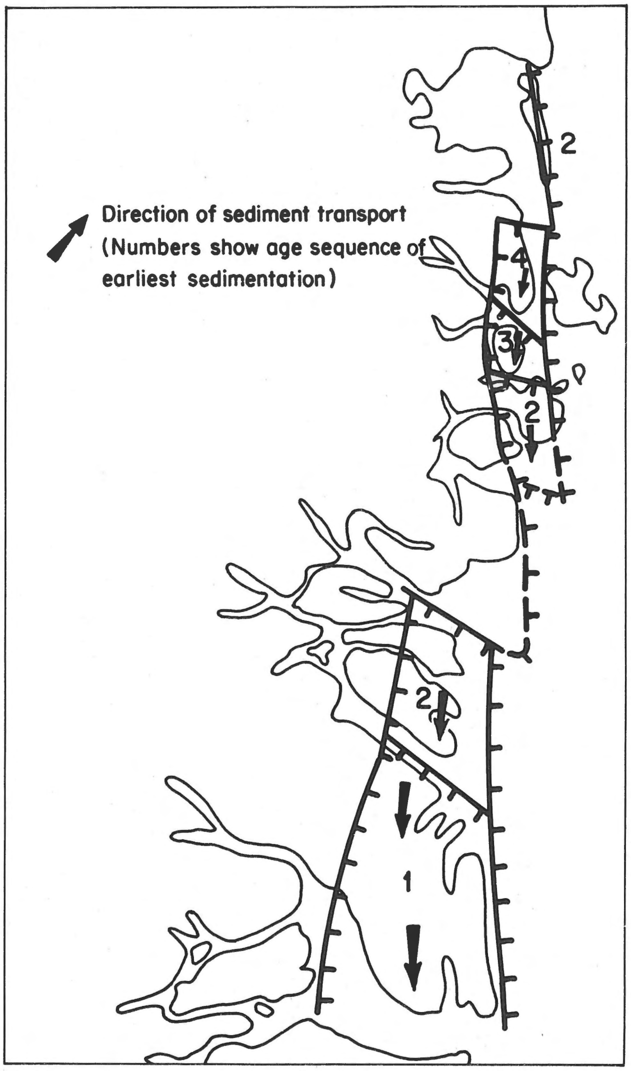


Fig. 9
Sketch map showing the fault-controlled Jurassic basins in East Greenland.

lyk, in press). (There is in many sections a bimodal pattern, with a subordinate northerly component interpreted as being due to tidal flood currents.) The southerly transport pattern has also been recognized in the Oxfordian Muslingebjerg Member of Hochstetter Forland and in contemporaneous sandstones on Milne Land; it is also extremely characteristic of the Volgian Raukelv Formation and the Berriasian Hesteelv Formation in Jameson Land (Surlyk, 1973), and the Berriasian – Valanginian Hartzfjeld Formation in Milne Land (Sykes & Brand, 1976). Although these sandstone formations are marine, they were laid down in very shallow water under fluviatile influence, and scattered coal seams and rootlet horizons occur in most units.

The Jurassic basin of Central East Greenland is abruptly terminated to the south by a 7 km thick pile of plateau basalts south of Scoresby Sund. In the same place there is a pronounced change in direction of coastline, and the angle between the northern and the southern coastline is 120°. Little is known about pre-Tertiary geology south of Scoresby Sund, but meagre geophysical evidence indicates the presence of a southern, coast-parallel Mesozoic basin and a few outliers are exposed in the Kangerdlugssuaq area (e.g. Soper *et al.*, 1976).

It has been suggested that the Mesozoic grabens in the North Sea and the North Atlantic were formed as a result of mantle doming and consequent rifting and formation of trilete junctions, the main sediment filled grabens representing "failed arms" (e.g. Whiteman *et al.*, 1975). It might be interesting to compare the East Greenland Basin data as presented above with the model. The arms of trilete junctions, formed as a consequence of updoming, are widest at the centre of the dome and get narrower away from the centre. Ideally, three rifts are formed with an angle of 120° between each arm. Many well documented "failed arms" (e.g. the Niger Delta) are characterised by longitudinal transport towards the centre, where major deltas are formed.

There is thus a perfect agreement of the East Greenland Jurassic basin with the main characteristics of "failed-arm" sedimentation. (The only exception to the classical aulacogen is the lack of an orogen placed at right angles to the aulacogen.)

The large-scale geometry also fits, as the two roughly coast-parallel basins form an angle of 120° – although very little is known of the southern basin. Theoretically, a third arm should be expected trending SE – SSE. This can hardly be tested, since this area is now situated on the other side of the Atlantic Ocean owing to much later Cenozoic spreading along axes parallel to the two other basins. If a pre-drift map is studied, the theoretical third arm, however, should be found in the area of the Viking Graben (Fig. 10). The orientation of the Viking Graben is more N-S than the ideal SE – SSE orientation of the third arm, but it is believed that this arm may be represented by part of the complex of grabens running more or less N-S west of Norway.

The model proposed here for the structure and evolution of the East Greenland Mesozoic Basin originated from a detailed study of fault patterns, stratigraphy and sedimentary facies. The model predicts two basins trending roughly WSW and SE away from a centre immediately south of Scoresby Sund. It predicts also that each basin evolved by progressive down-faulting away from the centre and with longitudinal transport of coarser sediments towards the junction area.

The model may have great predictive power in the study of the Jurassic sand body geometry in the oil fields of the northern North Sea. Thus the major sand bodies should be investigated for longitudinal transport and thereby longitudinal changes in grain sizes and thickness etc.; basin extension may have taken place by progressive down-faulting of blocks along the length of the grabens.

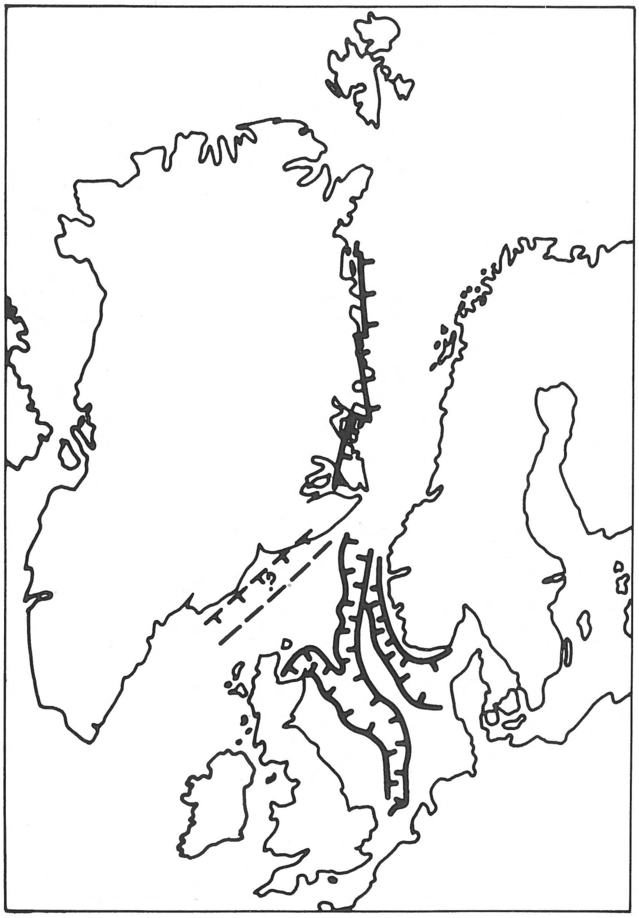


Fig. 10
Sketch map showing basin formation and postulated Jurassic trilete junction south of Scoresby Sund.

CONCLUSIONS

Mesozoic faults in East Greenland show distinct orientation patterns which correlate well with Caledonian and older lineaments. It is consequently suggested that, although the Mesozoic faulting in itself is unrelated to basement structures, the actual orientation of the faults is strongly dependent on the basement anisotropy.

The Mesozoic faults are normal, dip-slip types with throws up to 4 km – mainly accomplished by rotation of fault blocks. Strike-slip faults have not been recognized, but their existence cannot be totally excluded.

The main fault episodes can be dated as: Middle Triassic, Rhaetic, Bathonian, Callovian (?), early Oxfordian, late Oxfordian, early Kimmeridgian and particularly the Volgian – Valanginian. The last phase is the most important Mesozoic tectonic phase in the region and in some areas it resulted in strong antithetic block rotation owing to a crustal extension of 6%. The Cretaceous was relatively quiet, but faulting took place in the Aptian, Albian, and Turonian.

A general model for Jurassic sedimentation and tectonics in East Greenland is proposed. The initial basin formed by faulting along mainly N-S trending lines accompanied by slight westwards rotation of the fault blocks. In this way a number of N-S elongated depositional troughs were formed. This pattern already started to develop in the Early Carboniferous and continued throughout the late Palaeozoic and Mesozoic. The trough axes were orientated N-S and were located over the western down-tilted parts of the blocks, whereas the eastern block margins formed mountain ridges, elongated islands, peninsulas, or submarine shoals (depending on the degree of submergence). Subsidence took place mainly by gradual movements along the faults, only in certain periods interrupted by strong fault activity, for example at the Jurassic/Cretaceous boundary.

The general N-S fault pattern was cut by a number of NW-SE trending faults which downthrow to the south. These postulated faults are mainly located in the present fjords: Kong Oscars Fjord, Kejser Franz Joseph Fjord, "Lindemans Bugt", and Ardencaple Fjord.

In contrast to the N-S fault system, this system seems to have been activated in a series of violent movements, reflected by the pronounced stepwise reductions in thickness or disappearance of formations when passing the fault zones from south to north.

The major sediment transport pattern within this fault-controlled basin was consistently longitudinal from north to south. The sedimentary facies are of progressively more proximal nature in a northwards direction within each "en echelon block". The only exception is the syntectonic submarine fan sediments deposited laterally from the fault-scarps formed by strong antithetic Volgian - Valanginian block faulting.

Because of the graben geometry, longitudinal north to south infill, triangular shape being broadest to the south, and the progressive northwards basin extension by block faulting, the Jurassic basin possesses the main characteristics of a "failed arm" situation. A Mesozoic trilete junction is postulated in the area south of Scoresby Sund where the coastline makes a sharp 120° bend. The southern arm is paralleled by a little known offshore Mesozoic basin. Theoretically a third arm should be expected trending roughly SE. In a pre-drift reconstruction this third arm may correspond to parts of the Viking Graben complex.

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