Caledonides in Scandinavia compared with East Greenland

ANDERS KVALE

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The relative positions of Greenland and Scandinavia in pre-Tertiary times is discussed, and a modification is proposed of the map by Bott and Watts, based upon a study of the 500 m and 1000 m depth contour lines. A possible left-lateral displacement of the Vöring plateau along a proposed continuation of the Great Glen Fault is suggested. Assuming the relative positions of the two continents as outlined, the history of deposition in late Precambrian to Devonian times and events during the Caledonian orogeny in Scandinavia are reviewed and compared with East Greenland. The need for more information about the Scandinavian Caledonides is emphasized.

Anders Kvale, Geologisk institutt, avdeling A, Universitetet i Bergen, N-5014 Bergen, Norway. March 5th, 1975.

In 1911 Wegener proposed his hypothesis of continental drift, which for many years was met with scepticism or rejected by most geologists. As late as 1956 de Sitter (p. 489) stated that "the theory has hardly any adherents now".

During the last 10 to 15 years, however, a significant change has occurred in the attitude of geologists to the idea of large scale movements of continents. The ever increasing information about the earth's crust beneath the oceans, which has been provided by geophysical investigations and by the study of drill cores, has convinced most geologists that large scale movements of the continents must have occurred. The theory of plate tectonics has provided a plausible explanation to the problem of forces and to how such movements may have been mechanically possible. Today we may reverse de Sitter's statement and say that "the theory has hardly any opponents now".

As to the North Atlantic Ocean, it now seems likely, that Greenland and Scandinavia began to drift apart about 63 million years ago. This is suggested by the fact that the oldest magnetic reversals which have been found in the oceanic crust between Greenland and Northern Norway have number 24, (Talwani pers. comm.) We may therefore assume, that the distance between the east coast of Greenland and the west coast of Norway, which today is between 1200 and 1500 kilometers in pre-Tertiary times was, for the greater part of the coast lines, probably between 250 and 350 kilometers. These figures should be borne in mind in all our discussions of the correlation of larger features in the Caledonides on both sides of the North Atlantic.

The first geologist who discussed the consequences of continental drift for our understanding of the Caledonides in Greenland and Scandinavia was O. Holtedahl (Bailey and Holtedahl 1938), fig. 1. He emphasized, that the thick series of limestone and dolomite, which occur in East Greenland and Northern Norway, would have been closer together, if continental drift could be assumed.

In this paper firstly the relative positions of Greenland and Scandinavia in Caledonian times will be discussed, then the main features of the Scandinavian Caledonides will be outlined and comparisons made with East Greenland, keeping in mind the assumed relative positions of the two continents.

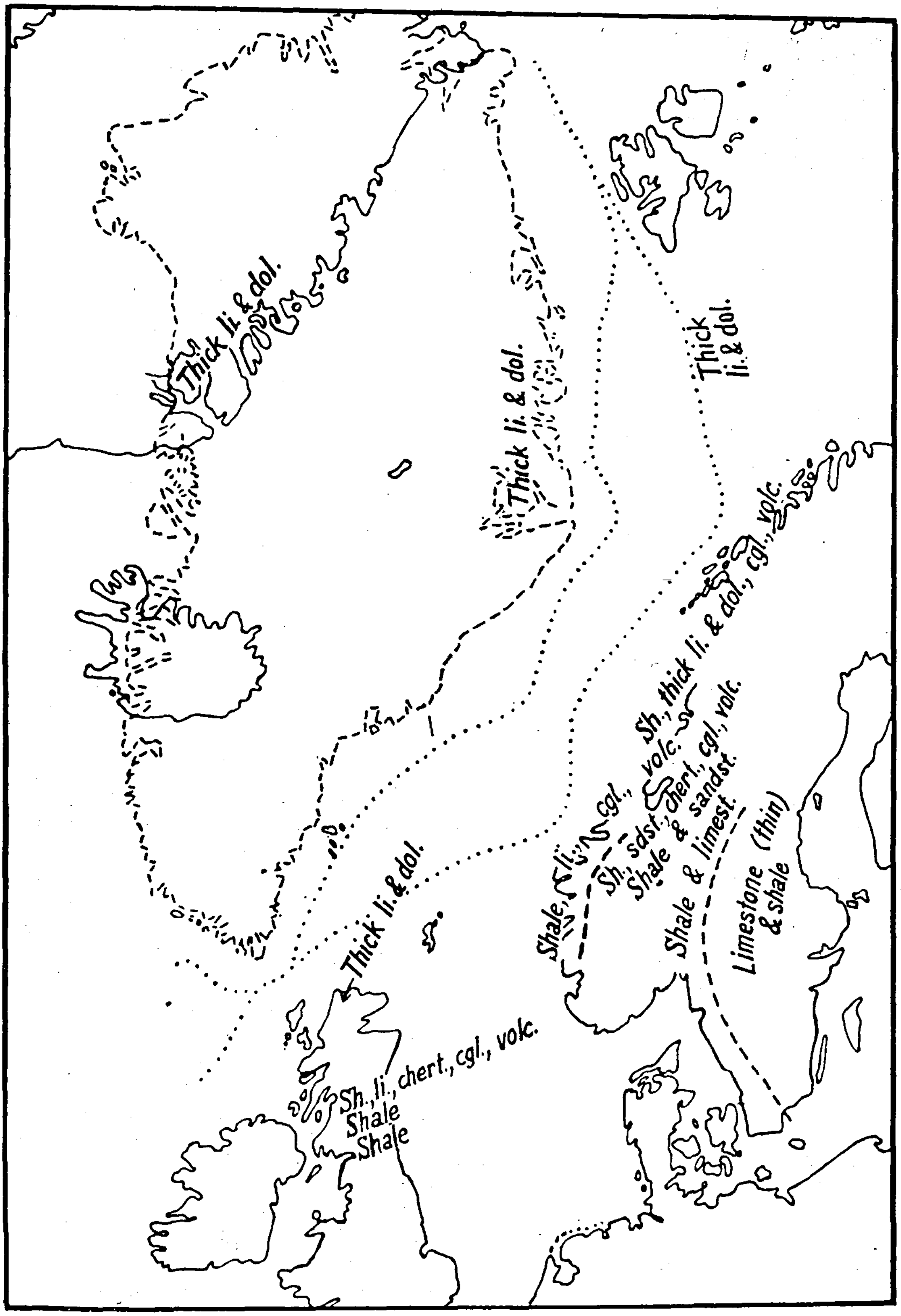
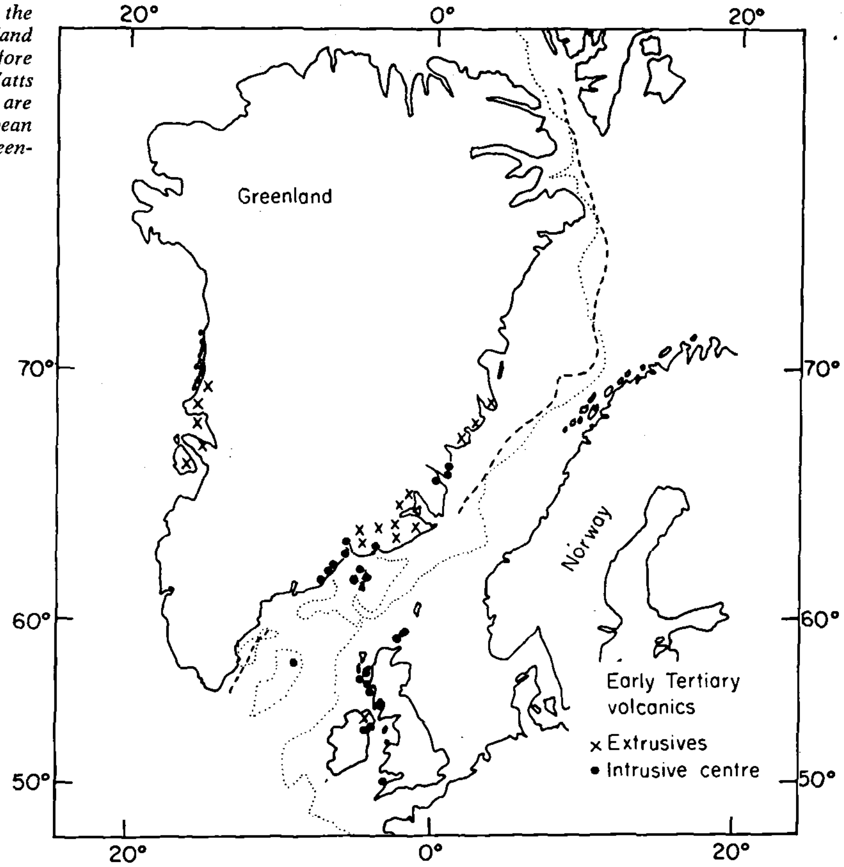


Fig. 1. Lower Ordovician facies-belts in North-west Europe. A pre-continental drift position of Greenland is suggested. (After Holtedahl in Bailey & Holtedahl 1938).

Fig. 2. Reconstruction of the relative positions of Greenland and North-west Europe before 65 m.y. ago after Bott & Watts (1971). 500-fathom contours are shown for the North European shelf (dotted) and for the Greenland shelf (dashed).



Relative positions of Greenland and Scandinavia in pre-Tertiary times

These positions have in recent years been discussed by various authors. Bullard et. al. (1965) presented a map of the pre-drift reconstruction, which was subsequently revised by Bott and Watts (1971). The best fit was obtained by rotating Greenland 14° about a pole situated at 58°N and 117°E (fig. 2). As a result Scoresby Sund was positioned opposite the Trondheimsfjord or about 700 km south of its position in Holtedahl's reconstruction.

Both Bullard et. al. and Bott & Watts used the 500 fathom depth contour as a guide line for obtaining the best fit. In a map published by Renard and Mallot (1974) the two continents are in very nearly the same relative positions as proposed by Bott and Watts.

The map published by Bott and Watts was constructed using Mercator's projection, which is not useful for our purpose. Eggvin et. al. published in 1963 a map of the Norwegian Sea in a conical projection, and his map is used in the following attempt at a reconstruction.

In fig. 3 the two continents are placed according to Bott, and the 500 m and 1000 m depth contours in Eggvin's map are drawn. These two contour lines give the approximate position and width of the continental slope. The contour lines fit remarkably well, considering what may have happened during the 63 million years since the parting began, of movements in the ocean floor, of submarine erosion, and of deposition during the Pleistocene glaciations.

The coincidence, according to the present reconstruction, is so good that it seems likely, that these lines may well indicate the pre-drifting positions of the continents.

In the following map lines have been drawn

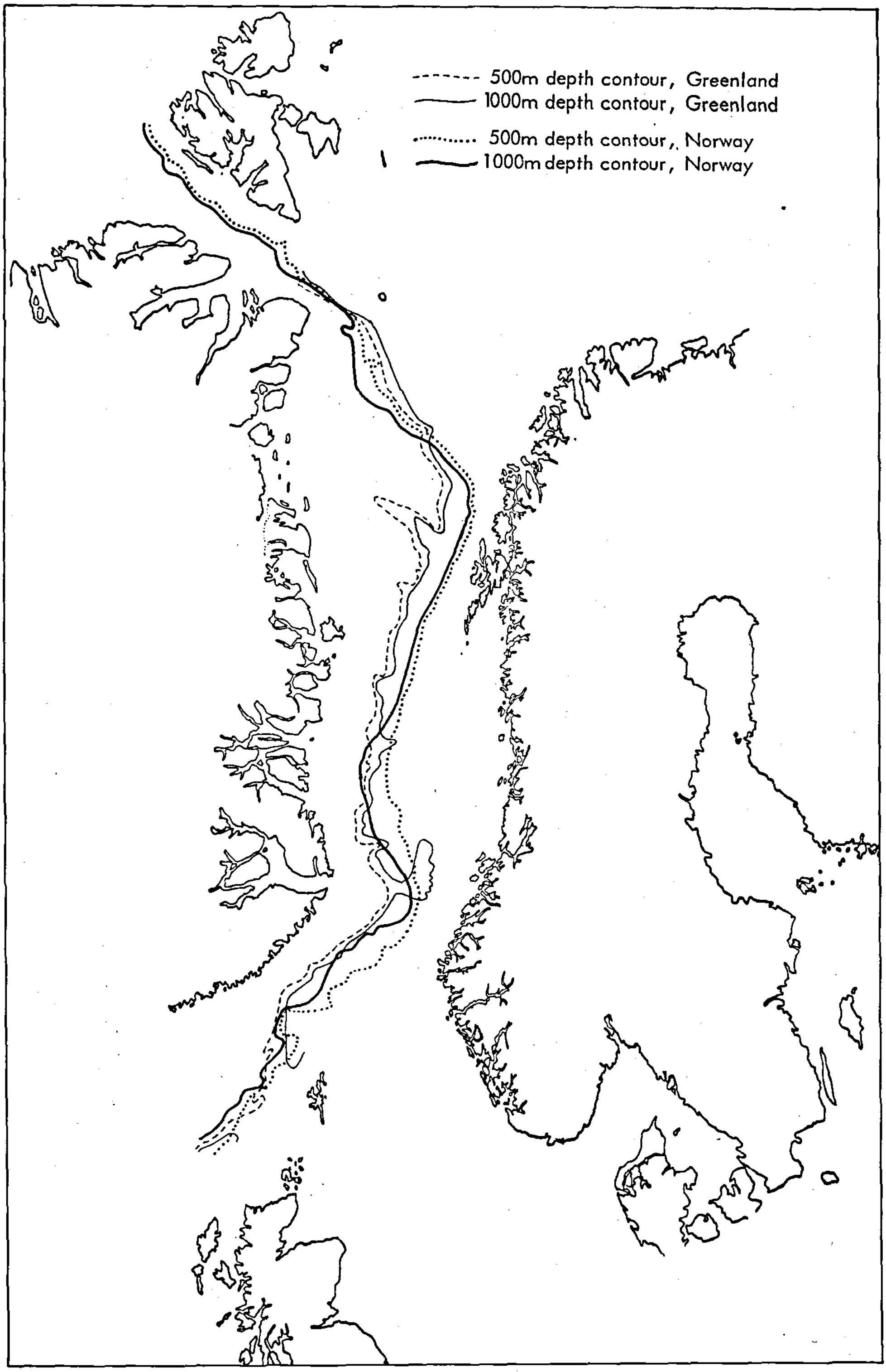


Fig. 3. 500 m and 1000 m depth contour lines outside North-west Europe and East Greenland with the two continents in the positions assumed by Bott & Watts.

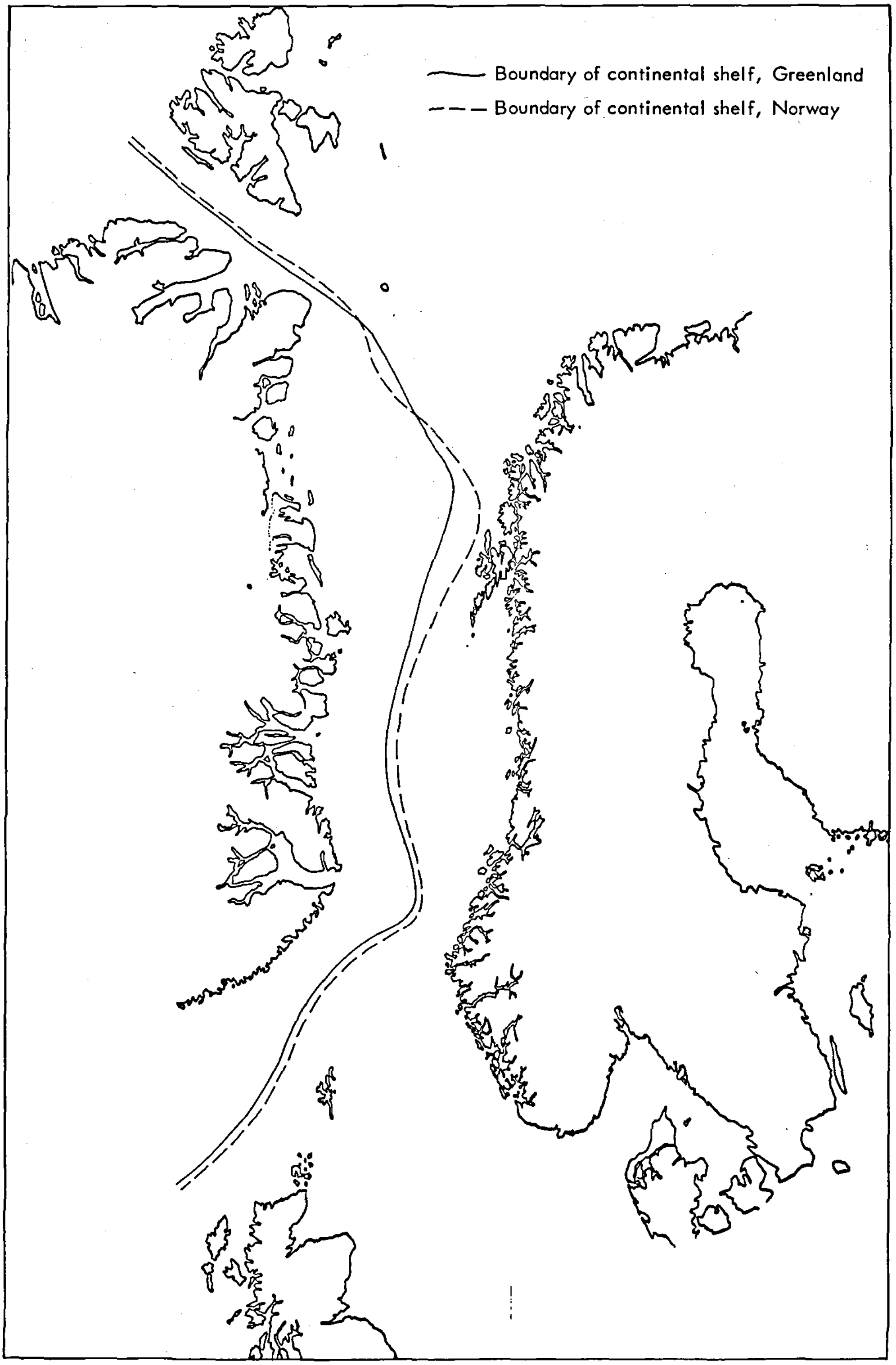


Fig. 4. Assumed boundaries of continental shelves outside North-west Europe and East Greenland.

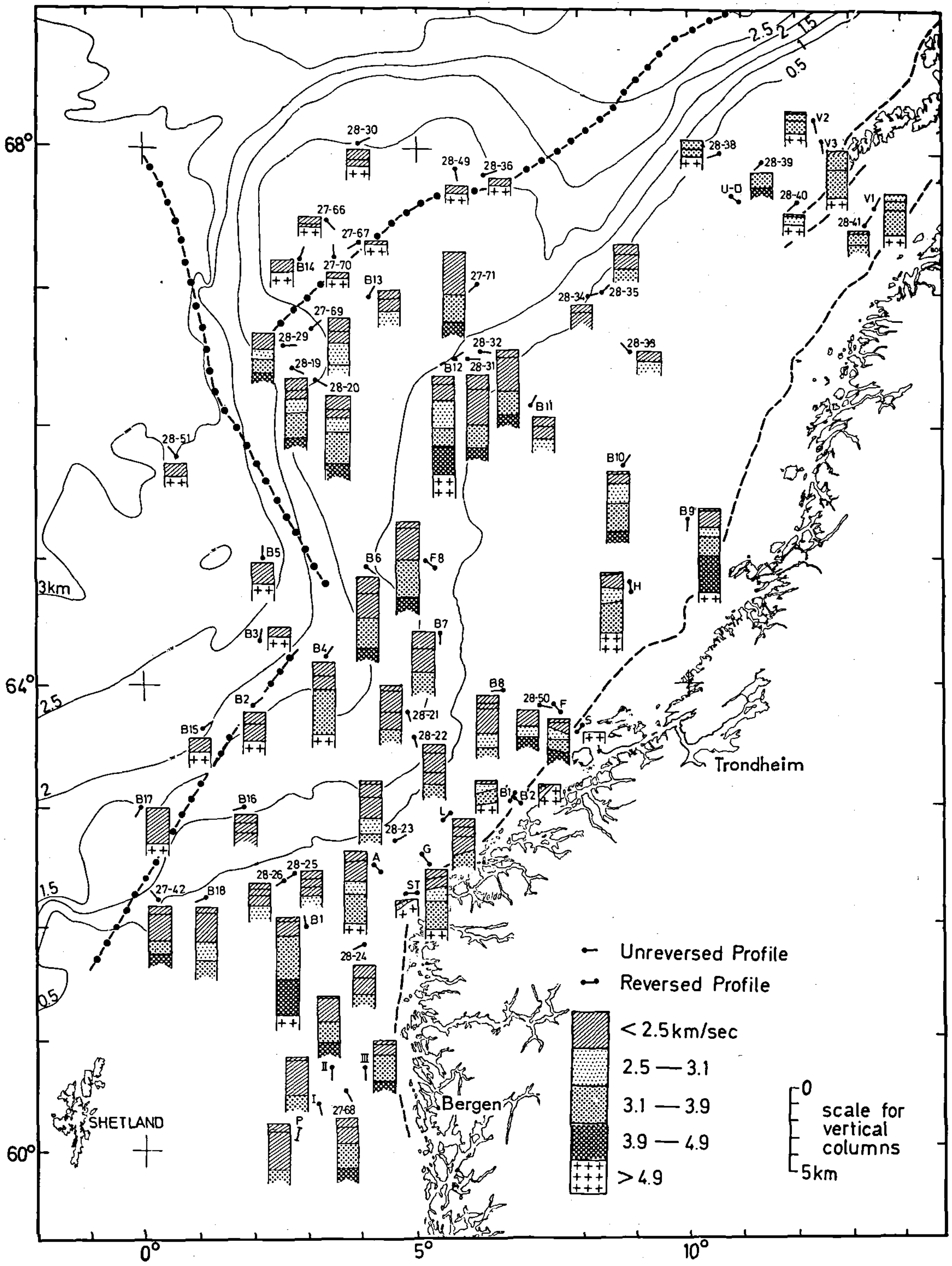


Fig. 5. Map showing seismic refraction data from Norwegian continental shelf between 60° and 68° N. From Sundvor et. al. (1974).

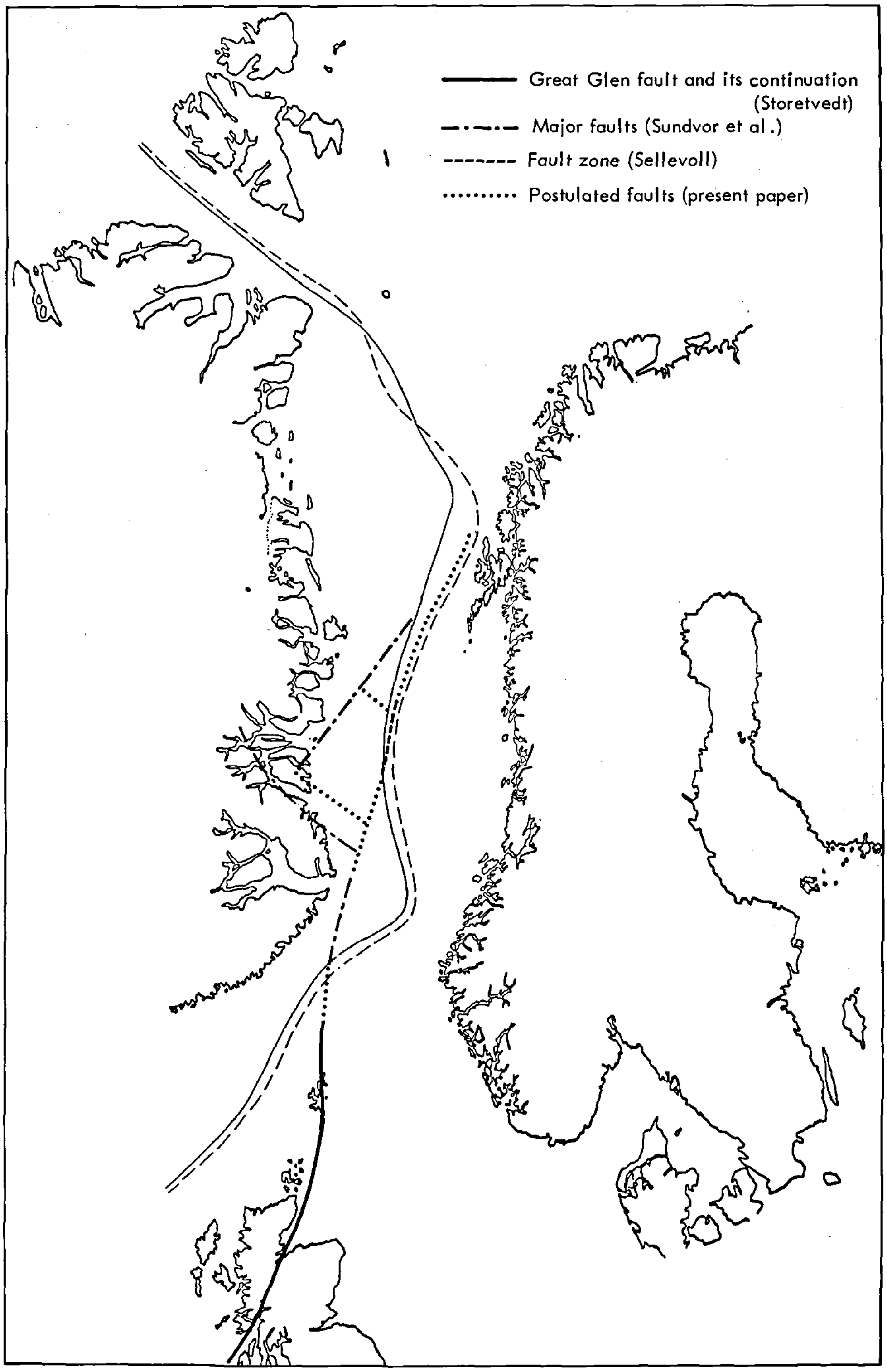


Fig. 6. Map showing continuation of the Great Glen Fault according to Storetvedt (1974), faults on the Norwegian continental shelf according to Sundvor et. al. (1974), fault according to Sellevoll (1972) and faults suggested in the present paper.

near the 1000 m depth contours, and these lines are taken to represent the boundaries of the continental shelves, fig. 4.

A more reliable indication would, however, be to compare the boundaries between continental and oceanic crust on both sides of the North Atlantic Ocean. At present very little is known about the composition of the continental shelf east of Greenland, but interesting information about the shelf outside Norway has been obtained through seismic investigations during the last few years, and through the drilling by the Glomar Challenger Expedition in August 1974. Important papers were published by Talwani and Eldholm in 1972 and by Sundvor et. al. (1974), fig. 5.

The seismic investigations have proved the existence of an important boundary line below or near the continental slope. East of this line Mesozoic and Paleozoic sediments were deposited on basement. West of this line Tertiary sediments were deposited directly on basement. The Glomar Challenger Expedition found that west of the line Eocene sediments were lying on a tholeiitic basalt, an indication that the crust west of the line is oceanic. East of the line none of the holes penetrated through the Eocene sediments, (Nilsen pers. comm.).

The Vöring plateau, however, forms an important exception to the coincidence of the boundary line with the continental slope. The Vöringbanken lies beneath a water depth of more than 1200 m, and is positioned west of the continental slope. But the assumed boundary between continental and oceanic crust goes in the western part of the plateau, and if we join the two continents as proposed, the Meso-

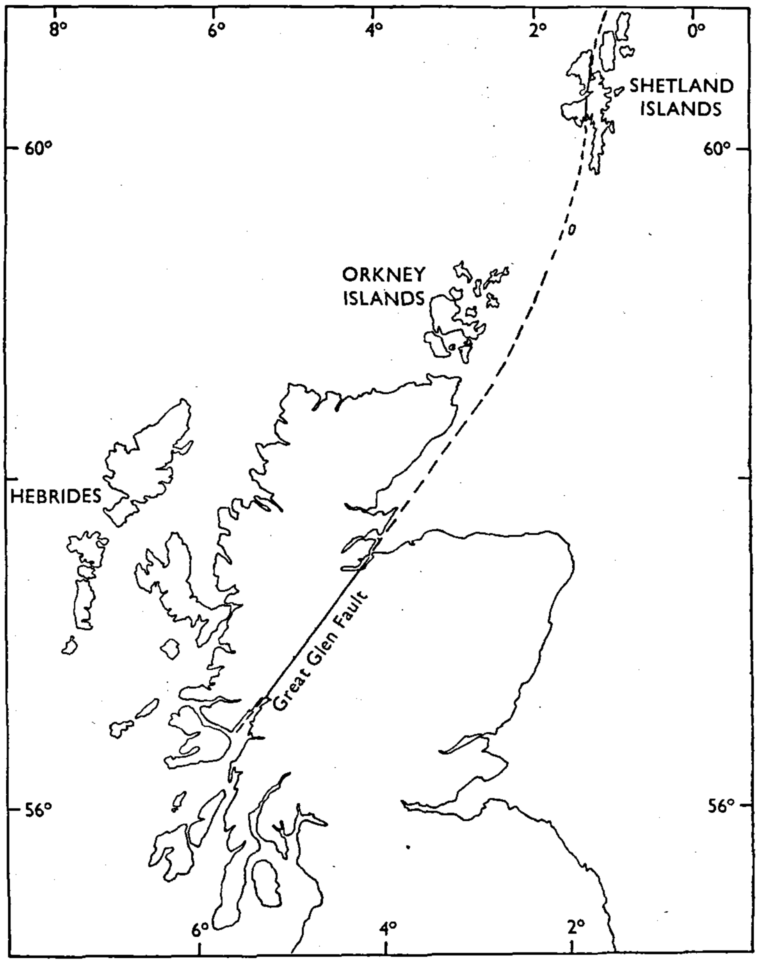


Fig. 7. Sketch map of Northern Britain showing the trend of the Great Glen Fault and its possible contination to the N. After Storetvedt (1974).

zoic and Paleozoic sediments of the Vöring plateau will north of Scoresby Sund reach about 100 km west of the present coast line, fig. 6.

In order to avoid this overlapping it would be necessary to separate the continental shelves by at least 200 km. The absence of continental crust south and north of the Vöring Plateau would then become a difficult problem to explain. An alternative explanation would be to assume that large-scale horizontal displacements had taken place in this part of the North Atlantic. There is, actually, some evidence in favour of such movements. In 1946 Kennedy found geological evidence for sinistral movements totalling about 100 km along the Great Glen Fault. His idea has been accepted by some and rejected by others. Flinn (1970) considered that the Great Glen Fault continues through Shetland. Storetvedt (1974) on the basis of paleomagnetic evidence indicated that sinistral movements in post-Devonian times totalling 200 to 300 km had occured along the Great Glen Fault and its continuation through Shetland, fig. 7. Sellevoll (1972) found that the depth to Moho was 26 to 28 km below the continental shelf east of the Vöring Plateau, fig. 8. As Hinz

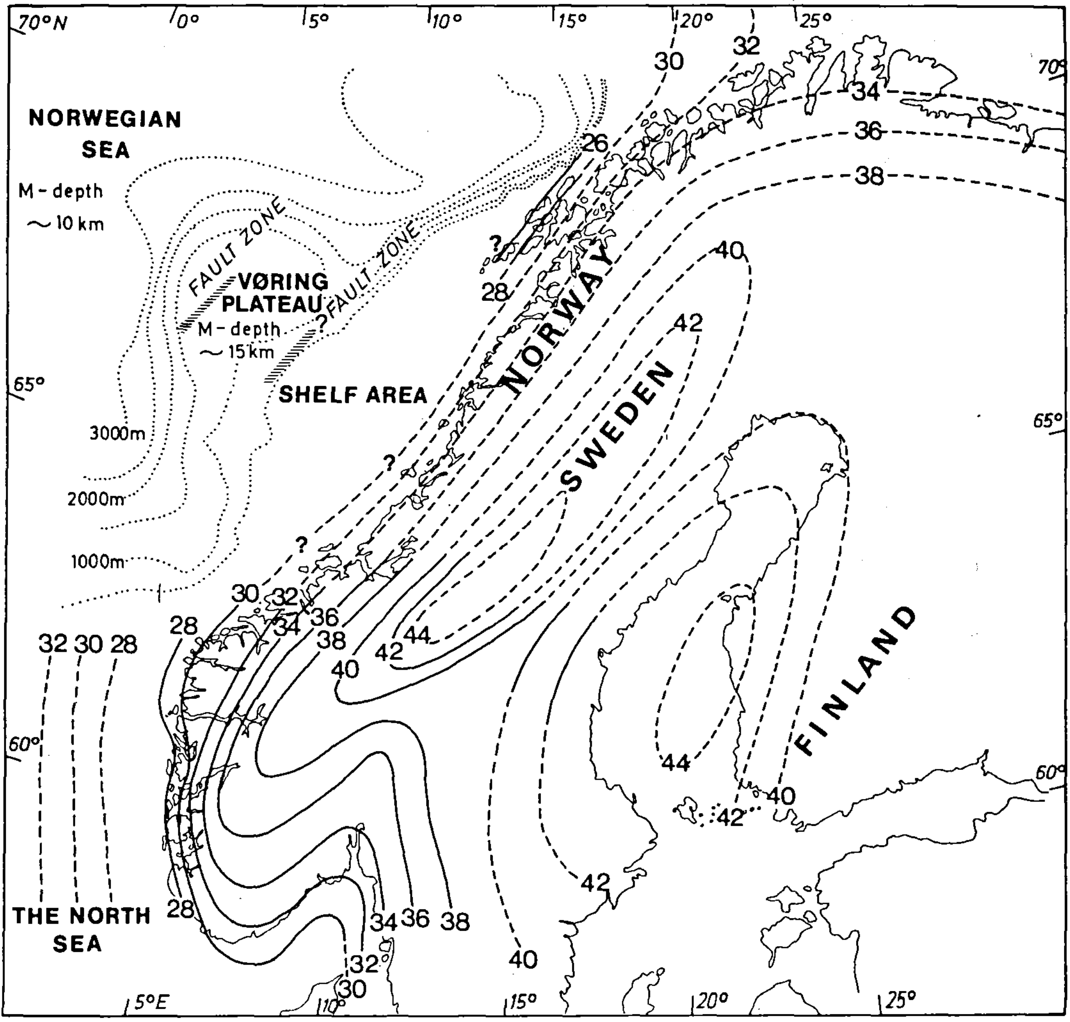


Fig. 8. Thickness of the earth's crust in Fennoscandia (in km.). After Sellevoll (1972).

(1972) had found that the depth to Moho was only 15 km below the Vöring Plateau, Sellevoll postulated a fault below the continental slope to separate the two types of crust.

In fig. 6 is shown the Great Glen Fault and its northward continuation as well as the western boundary of the continental crust further north as given by Sundvor et. al. (1974). It will be seen, that the two lines fit remarkably well. If we extrapolate the line northward, it joins the fault assumed by Sellevoll and it continues in the western boundary of the Norwegian continental shelf north of Vöringbanken. (Gjöystdal, S. and Husebye, E. S. (pers. comm.) have found that in recent years the epicentres of several earthquakes were located at or near the steep continental slope north-east of Vöringbanken.)

Dearnly (1962) assumed sinistral displacements of 125 km along the Minch fault between the Hebrides and the mainland. A continuation of this fault would fit even better with the faults further north than a continuation of the Great Glen Fault.

Some authors have seen a continuation of the Great Glen Fault in faults in Northern Ireland. Phillips et al. (1960) suggested that the Hampden fault in New Foundland may be a continuation of the Great Glen Fault, although the movement on the former is dextral. Whether these faults are continuous or not it seems quite clear, that a zone of strike slip faulting can be traced from the New Foundland area to Northern Ireland and Scotland, and that it may continue northward west of the Norwegian coast to about 70° N. The length of the fault zone from Ireland westward is 1750 km in the reconstruction by Phillips et. al. The length of the fault zone from Ireland to 70°N is about 1650 km. The total length of the zone of strike slip faulting may thus be at least 3300 km.

In fig. 9 the northwestern part of Scotland has been moved northward about 200 km. If we try to move it further, Shetland would enter the continental shelf outside Greenland. Even a shorter displacement would bring the shelf west of Shetland in collision with the shelf east of Greenland. But as the extent of the continental crust east of Greenland is not known at present, any discussion of the maximum displacement possible would be of little value.

In the same figure the block of continental crust in the Vöring Plateau has been moved northward along a supposed continuation of the fault line. The fault lines in the map by Sundvor et. al. are not definitely fixed by the seismic profiles which were made. In fig. 6 a northward displacement of the fault along the southwestern border of the Vöring plateau is suggested. It is also suggested that the Vöring plateau is limited to the northeast by a parallel fault.

If the Vöring plateau is limited by faults as suggested in this map, a northward displacement of about 350 km would bring it well outside the coast of Greenland, and a displacement of about 450 km would make it fit into the bend of the continental slope north of Andöya in Northern Norway.

If this reconstruction is valid, it might explain why the continental slope lies only about 20 km outside Andöya, while elsewhere the distance is much greater. It would also make the traces of oil and gas, which the Glomar Challenger expedition (1974) found in Miocene diatomic ooze on the Vöring Plateau, still more interesting to the search for oil and gas on the continental shelf outside Troms.

The suggested displacement of the Vöring plateau would, however, not bring it outside the continental shelf of Greenland. But further speculations on this subject would be of little value. The point which I want to make is, that it seems possible, that the problem of the Vöring plateau may be solved by horizontal displacement along a fault which lies in the continuation of the Great Glen Fault. This means further, that our map of the relative positions of Greenland and Scandinavia in pre-Tertiary times may be sufficiently accurate to serve as a base for our comparison of the Caledonides on the two continents.

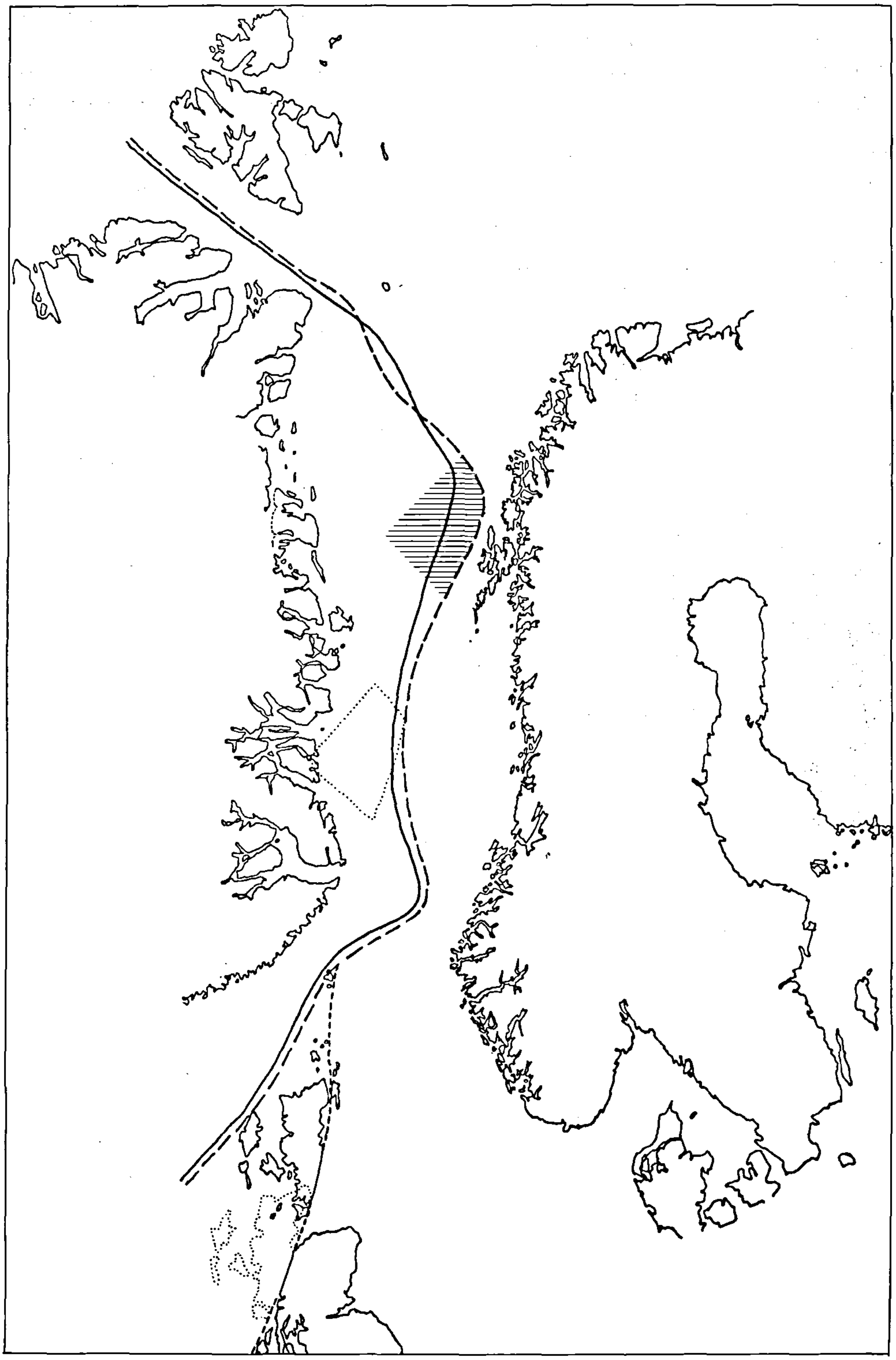


Fig. 9. Map showing suggested displacement of the Vöring plateau and displacement of North-west Scotland suggested by Storetvedt (1974).

Late Precambrian and Eocambrian deposits

The latest Precambrian orogeny in Scandinavia probably came to an end between 1000 and 1100 million years ago. Age determinations of post-tectonic granites have given figures as low as 850 million years (Broch 1964). Before the beginning of the Cambrian, erosion and denudation had brought these granites to the surface and produced a peneplane over at least the greater part of Fennoscandia.

The products of this large-scale erosion were deposited (fig. 10) in late Precambrian times as thick masses of clastic sediments in southern Norway, northern Sweden and eastern Finmark, as well as on the northernmost part of the Kola peninsula, 50 km east of Finmark. During the same period corresponding series of sediments were deposited in Spitsbergen, in the Eleonore Bay Trough and the Hagen Fjord Basin in Greenland, and in the north-west of Scotland.

In most basins deposition was continuous up into the Lower Cambrian sequence. Tillite horizons are found in the late Pre-Cambrian deposits in most of the areas, and if they are contemporaneous, as suggested by many authors, the deposits in the various areas may be correlated, fig. 11.

In southern Norway there is one horizon of tillite, in Finmark and in East Greenland there are two tillite horizons. Pringle (1972) determined the age of diagenesis of the Nyborg Shale between the tillites in Finmark to be 670 million years, a figure which is in good agreement with the ages of tillites in Congo and Australia.

Below the tillites there occur, in all areas, thousands of meters of sediments. In Finmark the Tanafjord series below the tillites is at least 1500 m thick. Pringle (op.cit.) found the age of diagenesis of shales near the base of the formation to be 810 million years. Two age determinations for shale diagenesis from the Torridonian in Scotland have given 810 and 995 million years (Moorbath 1973).

Ages of 600–1000 m. y. are reported from the Kola peninsula (Polkanov & Gerling 1960, Garris et al. 1964, Bekker et. al. 1970).

It has been widely stated, that the deposition of Eocambrian sediments marked the beginning of the Caledonian geosyncline. If we, however, consider the areal distribution of the late Precambrian and Eocambrian deposits, they are found to lie partly inside, partly outside the later geosyncline. They appear to have been deposited in separate basins during periods which may have lasted considerably longer than the Cambrian, Ordovician and Silurian periods together. In southern Norway the basins were formed by faulting along old NNW-trending lines of weakness. The younger Eo-Cambrian sediments have a wider distribution than the older ones, though over large areas in southern Norway Middle Cambrian beds trangressed directly on to the Precambrian.

Opinions have varied widely among Norwegian geologists as to the extent of Eocambrian rocks in Southern Norway. Beginning with Barth and Holtedahl (1938) several authors have postulated that large parts, perhaps most of the Northwestern Gneiss Area consisted of metamorphosed Eocambrian rocks. Some K-Ar age determinations seemed to support this view, though these are now best regarded as being due to Caledonian reheating. Whole rock Rb-Sr determinations in recent years have, however, given Precambrian ages as high as 1880 million years for rocks regarded by some authors as Eo-Cambrian (Brueckner 1972). At present it is doubtful whether there are Eocambrian rocks in other parts of the Northwest gneiss areas than along the northwestern border of the Cambro-Silurian schists between the Trondheimsfjord and the Jotunheimen.

We are thus returning to the older interpretation of the gneiss area as an area where Precambrian rocks have been reworked during the Caledonian orogeny.

In the coastal areas further north, from 65° to 70°, older geologic maps show large areas of Caledonian intrusive rocks, mainly granites and granitic gneisses, in the Lofoten area also syenites, monzonites and other rocks related to anorthosites. In the map by Holtedahl and Dons which accompanied Geology of Norway (1960), the rocks in the coastal areas between 68° and 70° were designated as Precambrian. Radiometric age determinati-

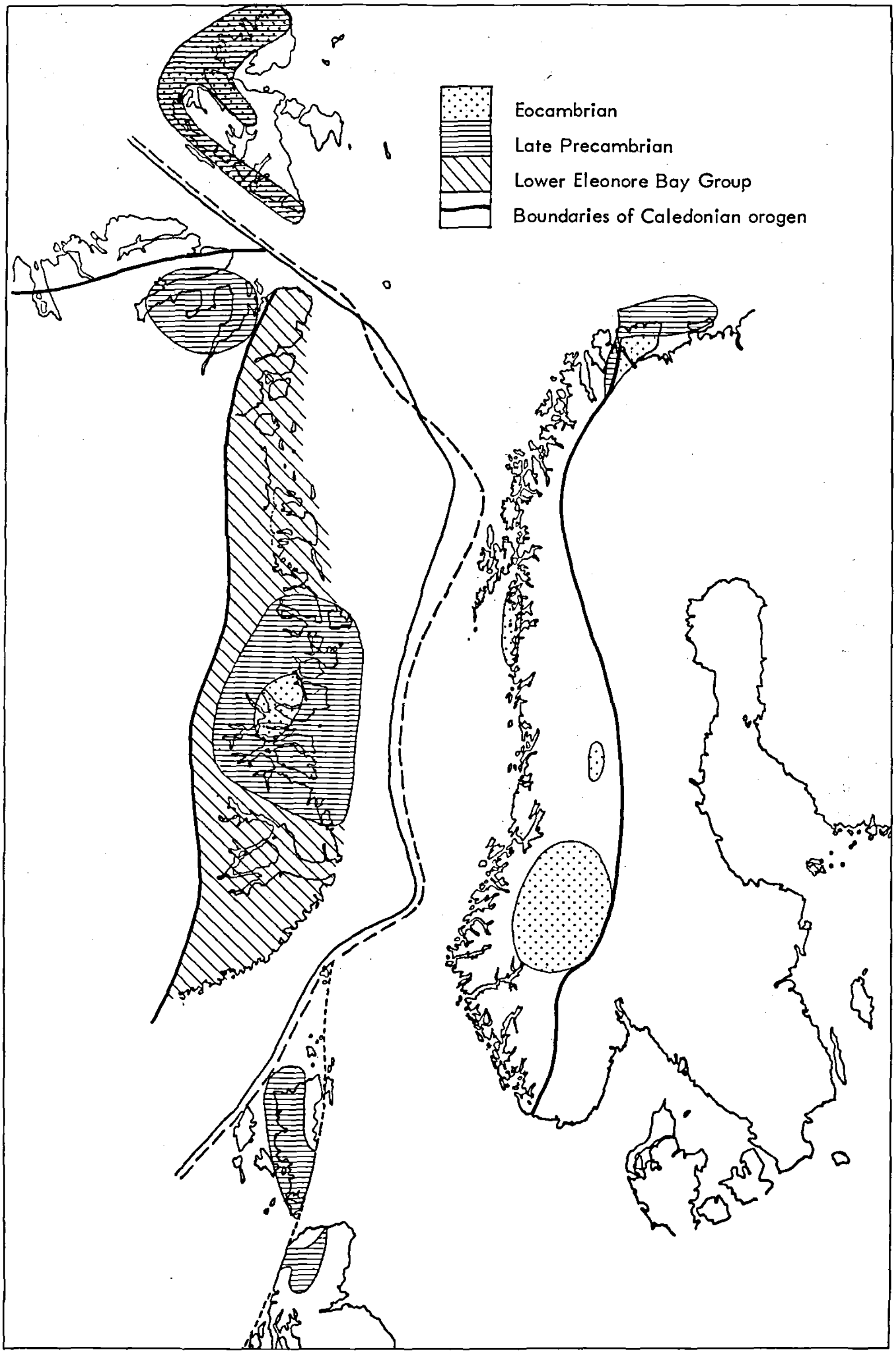


Fig. 10. Map showing known areas of Late Precambrian and Eocambrian deposits in North-west Europe and East Greenland.

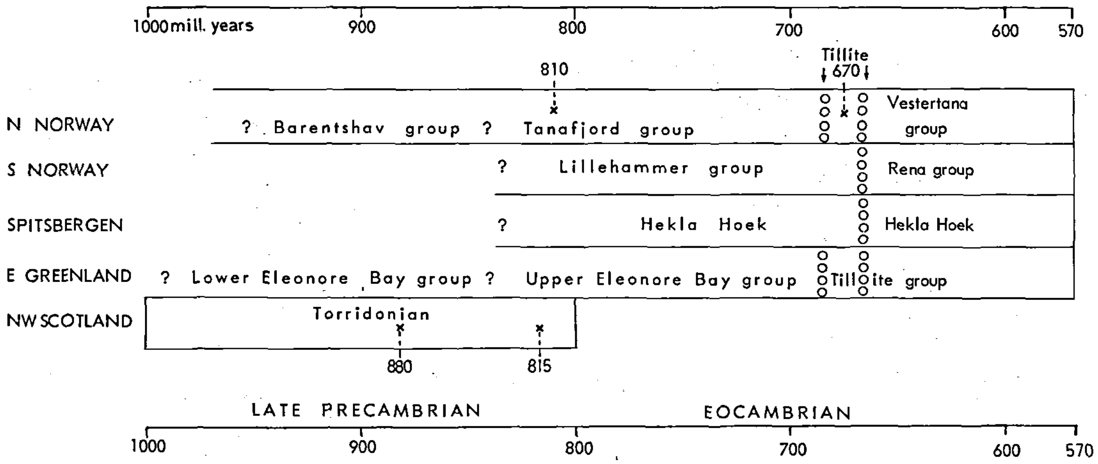


Fig. 11. Diagram of Late Precambrian and Eocambrian deposits in areas shown in fig. 10.

ons have later proved that at least the great majority of these rocks between 65° and 68° also are Precambrian (Heier & Compston 1969, Nicholson & Wilson 1973).

Precambrian rocks also appear west of Bergen and between Boknfjord and Hardangerfjord. An almost continuous ridge of Precambrian rocks would seem to exist along much of the length of the Scandinavian Caledonides. These rocks have been affected by varying degrees of tectonic reworking and metamorphism during the Caledonian orogeny. According to the present state of knowledge these rocks do not belong to overthrust units but are essentially in place as uplifted basement.

Cambro-Silurian deposits

In the Lower Cambrian uniform sediments were deposited over large areas, some of which were later to become the Caledonian geosyncline.

Störmer (1967) discussed the Caledonian geosyncline and foreland west of the Baltic Shield. He indicated on a map, fig. 12, his suggestions for the original positions of the various parts of the geosyncline, with from east to west the craton, the foreland, the miogeosynclinal and two eugeosynclinal belts with different stratigraphy. No deposits from a western miogeosynclinal belt have, however, been found in Scandinavia.

If we transfer Störmer's belts to the pre-drift reconstruction employed in this paper, (fig. 13) the western miogeosynclinal belt would be in Greenland. According to Haller (1970) it is difficult to characterize the Cambro-Ordovician deposits of East Greenland as either miogeosynclinal or eugeosynclinal, though the rocks generally show a miogeosynclinal aspect.

A study of the Cambro-Silurian sediments in the Caledonides of Scandinavia is, outside the Oslo area and Jämtland, hampered by two important obstacles:

1. Fossil localities are few and far apart (fig. 14), and many of the fossils are so deformed and metamorphosed, that an accurate identification is not possible.
2. Most of the rocks are allochtonous or parautochtonous. Thrust planes are numerous, though many of them are difficult to detect. Large-scale stratigraphic inversions occur in many areas, and many of the primary features indicating such inversion have been destroyed by deformation and metamorphism.

Lower Cambrian sandstones and shales are found in an autochtonous sequence along the eastern margin of the Caledonides from Central Norway to Finmark. The thickness varies from 45 m in the Mjösa district to about 250 m in Finmark. A Middle Cambrian transgression brought marine deposition to the Oslo area and probably to the whole of Western Norway.

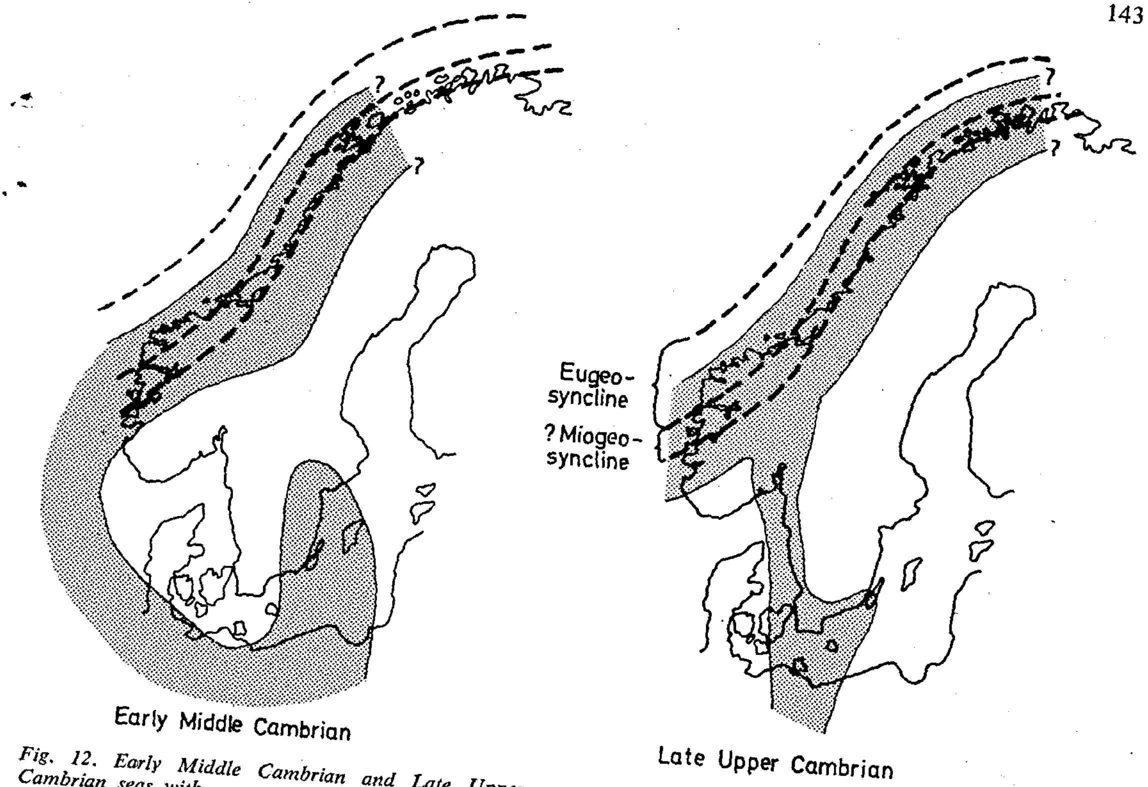


Fig. 12. Early Middle Cambrian and Late Upper Cambrian seas with geosynclinal belts. From Störmer (1967).

Störmer's maps, fig. 12, show the assumed extent of the Lower and Middle Cambrian seas, fig. 15. The Upper Cambrian and the lowermost Ordovician sediments are dark alum shales, rich in Carbon and Sulphur. They are found over large areas.

The total thickness of the Cambrian in the Oslo area is about 120 m. It is remarkable, that during a period of perhaps about 70 million years conditions seem to have been very uniform over large parts of Scandinavia, with a rate of sedimentation which, according to Björlykke (1974) in the Upper Cambrian of the Oslo area was about 1 mm in 1000 years.

The only evidence of different conditions comes from Western Finmark, where Sturt & Ramsay (1965) and Ramsay (1971) found an allochtonous series of 1000 m of psammites, schists, metagraywackes and limestones containing fossils of Lower to Middle Cambrian age.

After the deposition of the alum shales with Dictyonema the character of the sediments changed more rapidly, and local variations are found over relatively short distances. From this stratigraphic level onwards we can try to separate geosynclinal belts, figs 15 and 16.

The *foreland* sediments are found in the Oslo area and in Jämtland. Shales and limestones alternate, sandstones are rare. The Oslo area has a complete sequence up to and including the Downtonian. In Jämtland the youngest autochtonous rocks are Uppermost Caradocian, whilst Middle Llandovery fossils are found in overthrust rocks of the foreland type, (Kulling 1972).

The *miogeosynclinal* sediments are mainly shales and phyllites. Sandstones, partly calcareous, and limestone occur in some areas. Traces of volcanic rocks are found in the westernmost areas in southern Norway. Very few fossils have been found, the youngest being Llandeilian. In Norway there is no evidence of a sedimentation later than Middle Ordovici-

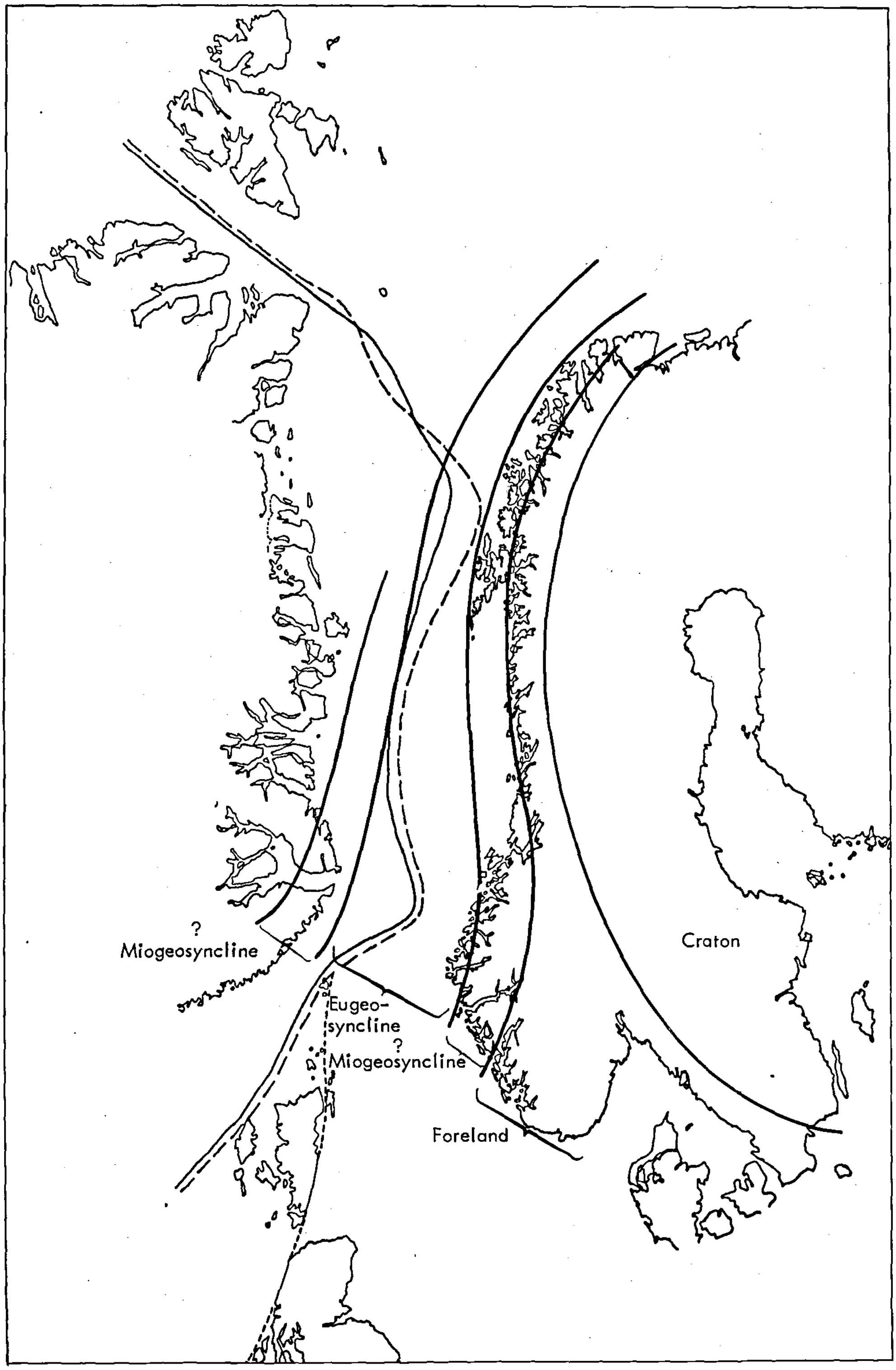


Fig. 13. Caledonian geosynclinal belts according to Störmer (1967) drawn on map showing assumed pre-Tertiary positions of Greenland and Scandinavia.

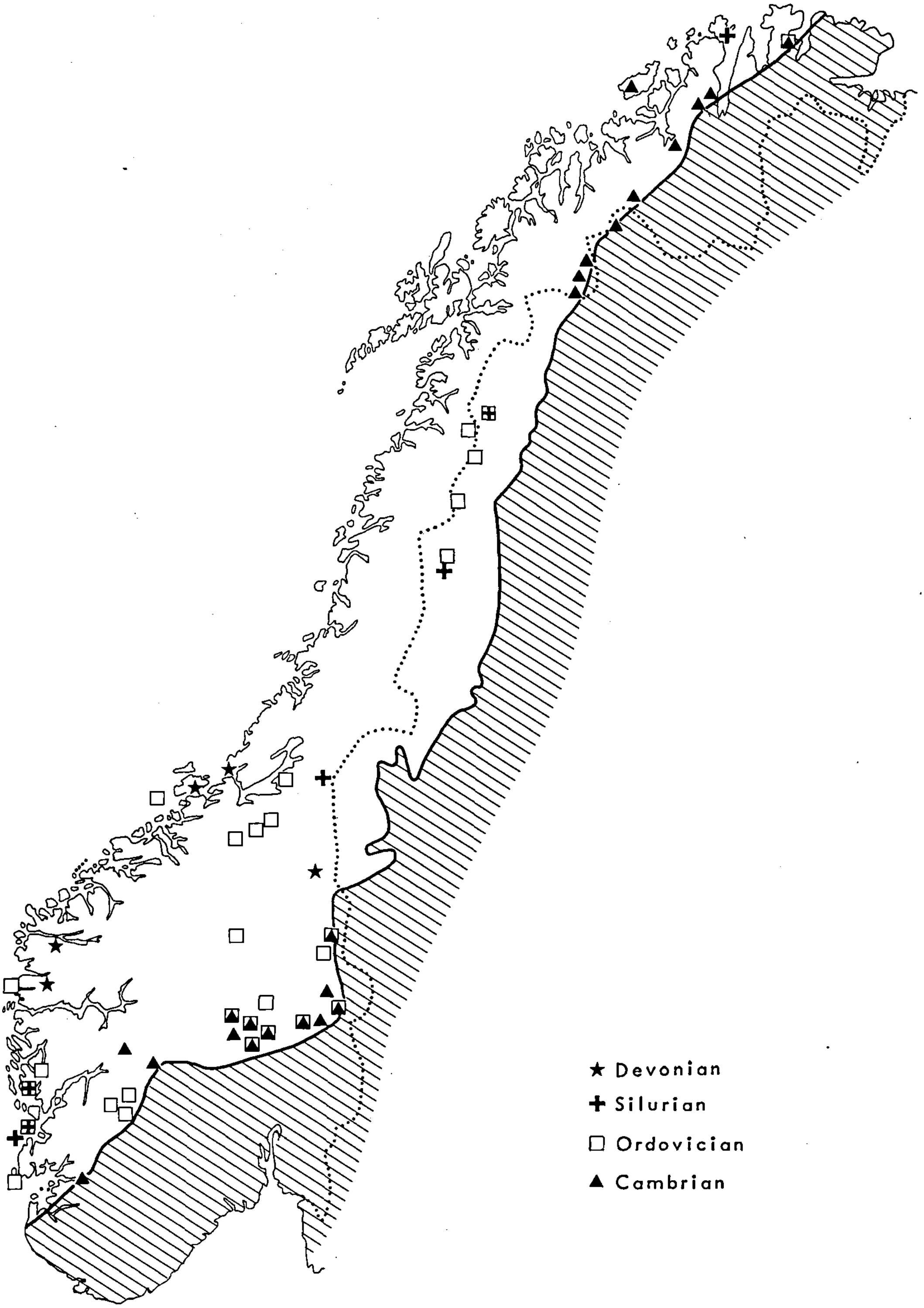


Fig. 14. Localities of fossils found in the Caledonides of Scandinavia. Foreland areas (Oslo area and Jämtland) not included.

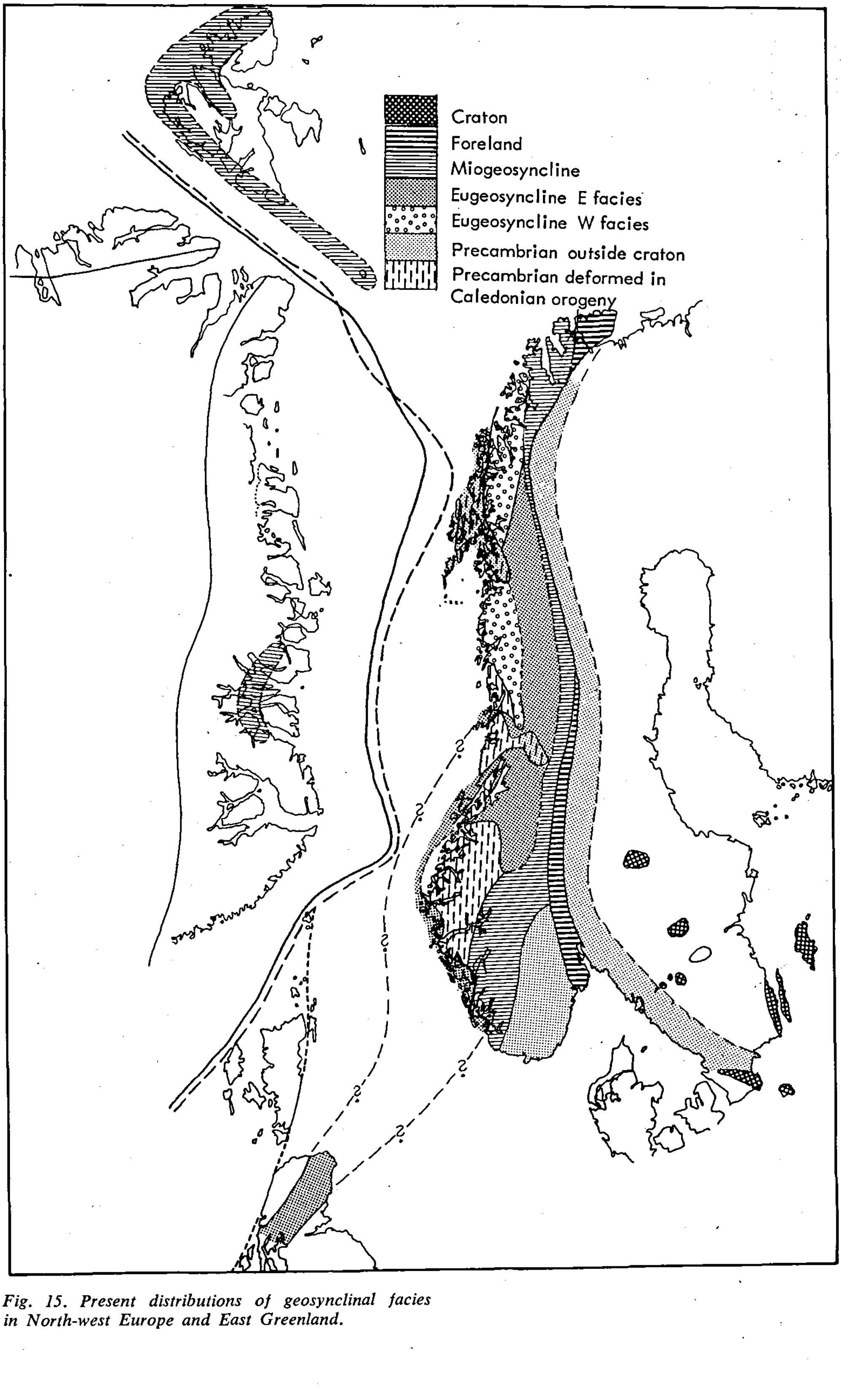


Fig. 15. Present distributions of geosynclinal facies in North-west Europe and East Greenland.

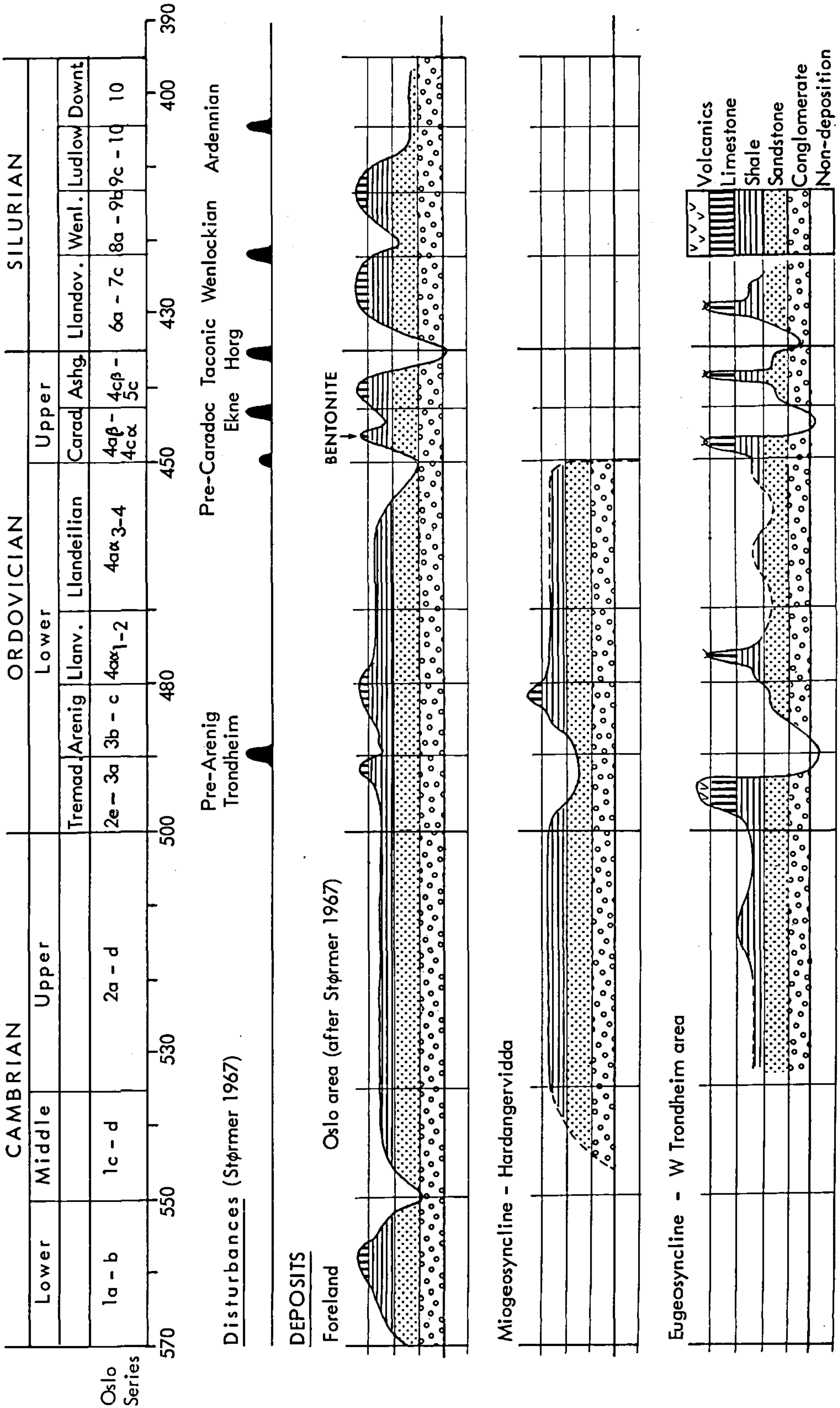


Fig. 16. Cambro-Silurian deposits in Norway.

an, while in Sweden miogeosynclinal rocks in the nappes contain fossils from the Lower Wenlock. (Kulling 1972).

The total thickness of the miogeosynclinal Cambro-Silurian sediments in Eastern Norway has been estimated at 400 to 500 m. The corresponding sequence in the Oslo area is approximately 400 m thick.

The *eugeosynclinal* series are characterized by a sequence which may be up to ten times the thickness of the foreland sediments, by great variations in lithology both spatial and temporal, by large amounts of volcanic rocks, and by basic and acid intrusions. We may distinguish between an eastern facies, which is typically developed in the Trondheim area, and a western facies, which is best developed in the Ofoten district of Nordland.

The *eastern facies* contains thick series of volcanic rocks. In the Trondheim area the thickness of the Tremadocian greenstones has been estimated at 3000 m, and volcanic rocks, partly basic and partly acid, are found also in the Llanvirnian, the Caradocian, the Ashgillian and the Llandovery. The sediments are polymictic and quartzitic conglomerates, sandstones, graywackes, shales and limestones. The sequence is different in the western and eastern parts of the Trondheim area, and it is different in the various parts of the Swedish Caledonides.

The youngest fossil-bearing rocks in the Trondheim area and in Western Norway are of Llandovery age, whilst in Sweden Wenlockian fossils have also been found.

The thickness of the limestones increases northward in the Trondheim area. This may indicate a beginning transition to the *western facies,* which occupies the coastal areas of Nordland and the greater part of Troms. It is characterized by thick masses of limestone and dolomite, and by a relative scarcity of volcanic rocks compared with the eastern facies.

This facies bears some resemblance to the Cambro-Ordovician of Spitsbergen and East Greenland.

The estimated thickness of about 7000 m has by Kulling (1960) and others been explained as due to a succession of nappes.

No fossils have been found in the rocks of this facies in Nordland. On the island of Smöla, west of the Trondheim area, limestones occur, and contain a Middle Ordovician fauna which differs from that of the Oslo area, but is similar to that of Björnöya, of northwest Scotland and of New Foundland. Other sediments and volcanics occur, and it has been suggested, that this series may belong to the western facies.

At Mageröy in Finmark fossils from the Llandovery (Henningsmoen 1961) occur in limestones and associated greywackes which form part of a nappe (Ramsay & Sturt in press). It is not known to which of the geosynclinal belts this nappe belongs.

Orogenic phases and disturbances

The periods of main tectonic activity in East Greenland and the British Isles are shown in fig. 17 and are compared with events in Scandinavia.

In East Greenland the main tectonic activity, according to Haller (1970), occurred in Upper Silurian times i. e. about 420 to 400 million years ago. "Late Caledonian Spasms" occurred at intervals throughout the Devonian, and "Minor Succeeding Episodes" occurred throughout the Carboniferous.

In the British Isles Bennison & Wright (1969) resolved the nine phases of orogeny which have been described from the Cambrian to the Devonian into two main periods of polyphase folding: early Ordovician metamorphism and folding in the Highlands of Scotland and in northern and western Ireland; and post-Silurian folding in the southern part of Great Britain.

In Spitsbergen Silurian fossils have not been found, and the deformation and metamorphism of the Hekla Hoek series is supposed to have occurred during the late Silurian Ardennian phase (Winsnes et. al. 1960).

When correlating geologic events in various areas one must always remember, that our methods of dating are still rather inaccurate. Events which we describe as simultaneous may have been separated by perhaps a few million years.

In Norway Th. Vogt (1929) indicated evidence for six periods of disturbance. Störmer

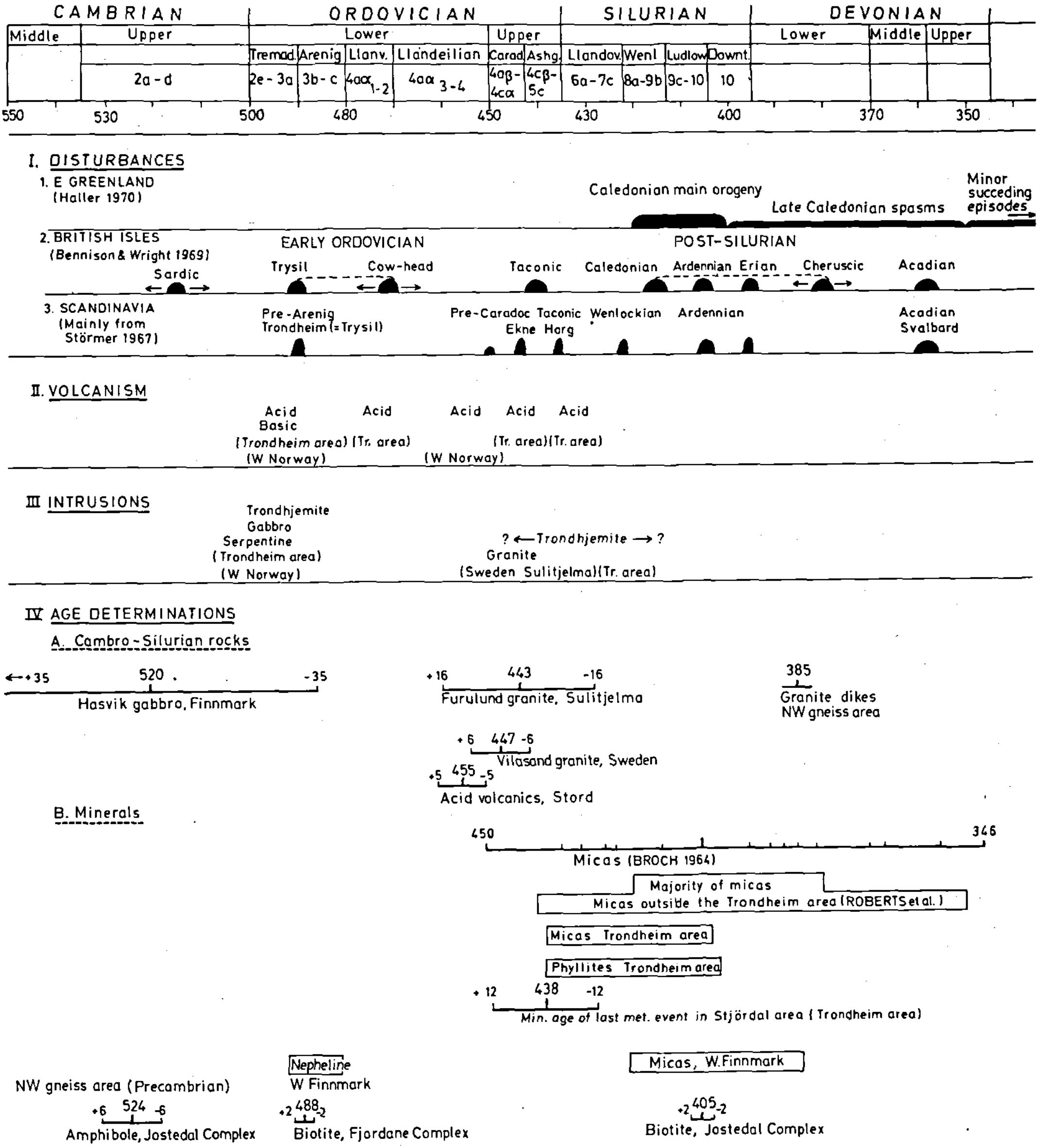


Fig. 17. Caledonian disturbances in East Greenland (Haller 1970), in the British Isles (Bennison & Wright 1969), and in Scandinavia (mainly from Störmer 1967). Periods of volcanism and intrusions in Norway. Radiometric age determinations from Scandinavia which are related to the Caledonian orogeny.

(1967) added two more, and his list is shown in fig. 17. Pringle & Sturt (1969) found evidence of an additional orogenic phase in Finmark.

The evidence for the orogenic phases discussed by Störmer has been stratigraphic, and mainly based on the widespread occurrence of conglomerates or on the evidence for periods of non-deposition which are believed to be contemporaneous. Some radiometric age determinations have been made on Caledonian rocks from Precambrian areas and on Precambrian rocks which have been re-heated by Caledonian metamorphism. Broch (1964) critically reviewed all age determinations which had been made on Norwegian rocks until then. He listed as reliable 13 determinations which may be related to the Caledonian orogeny. The ages varied from 346 to 450 m. y., all but two of them determined on minerals from Precambrian rocks, fig. 17. In addition he listed three determinations from 575 to 590 m. y., also on minerals from Precambrian rocks.

Age determinations after 1964 of probable Caledonian events are found in papers by Sturt, et. al. (1967), Bryhni et. al. (1971) (Precambrian rocks) Wilson, et. al. (1973) (metamorphism) and by Priem & Torske (1973) (volcanics). Also these dates are given in fig. 17.

The figure does not give complete information on determinations after 1964 which may be related to the Caledonian orogeny, but it is believed to be sufficient for the present discussion.

1. The first Caledonian event which is recorded in Scandinavia is the intrusion of the Hasvik gabbro in western Finmark. 530 ± 35 m. y. ago (Pringle & Sturt 1969). In Southern Norway a trace of this event may be found in amphibole from the Precambrian Jostedal Complex, where an overprinting event is dated at 524 ± 6 million years (Bryhni et. al. 1971). Both ages are probably Upper Cambrian. Neither in the Oslo area nor in the miogeosynclinal deposits are there recorded any indications of a disturbance during this period. At present, detailed knowledge of the Upper Cambrian stratigraphy in the eugeosynclinal deposits is so little, that no certain stratigraphic indications of this event are to be found.

2. The second event is the *Trondheim or Trysil disturbance.* The Tremadocian greenstones in the Trondheim area were intruded by trondhjemite. Subsequent uplift and erosion produced conglomerates (Venn and Stokvola), containing pebbles of volcanics and intrusives (Strand 1972). This event probably was accompanied by metamorphism.

The only radiometric age determination which may be related to this event seems to be that of a biotite from the Precambrian Fjordane Complex (Bryhni et. al. 1971), where an overprint at 488 ± 2 m. y. is recorded.

3. Störmer mentioned a *pre-Caradocian disturbance,* which is recorded in sandy beds in the northernmost part of the Oslo area. It is not known from elsewhere and was probably a minor event.

4. The pre-Ashgillian *Ekne disturbance* was more important. In the western Trondheim area it preceded the polymictic Volla conglomerate, which has a maximum thickness of 150 m.

In the coastal areas of Western Norway the Upper Ordovician polymictic Moberg conglomerate has a maximum thickness of perhaps 700 meters, which indicates a period of considerable uplift and erosion. The pebbles consist predominantly of Lower Ordovician volcanic and intrusive rocks, which were metamorphosed before erosion, (Kvale 1960). The metamorphism may be related to the Trondheim disturbance. Above the conglomerate lies a phyllite with grey limestone containing Lower Ashgillian fossils.

In Sweden the Ashgillian Voitja conglomerate is the most widely distributed conglomerate in the eugeosynclinal sequence. It is a quartzite conglomerate, which may be somewhat younger than the Volla and Moberg conglomerates. Whether it is related to the Ekne disturbance, or to the subsequent Horg disturbance, or to neither of them, is not known.

There is some evidence of igneous activity which may be related to this event. The Vilasand granite in Sweden is 447 m. y., (Gee & Wilson 1974), the Furulund granite in Sulitjelma is 443 m. y., and granitic dikes in Sulitjelma are 433 m. y. (Wilson et. al. 1973).

According to Wilson et. al. the minimum age of the last metamorphic event in the Trondheim area is 438 ± 12 m. y., which may indicate a connection with the Ekne disturbance.

5. The next event, *the Horg disturbance,* has been compared to the Taconic phase. In the central part of the Oslo area the uppermost Ordovician beds are sandy, and in the northern part deposits are lacking. In the Trondheim area, the quartzitic Lyngestein conglomerate was related to the Horg disturbance by Vogt (1929), though its age has been recently questioned by Oftedahl (1974). In the Bergen district the quartzitic Ulven conglomerate, which previously was also related to this event, is clearly younger than a phyllite containing Middle Llandovery fossils.

The status of the Horg disturbance is, therefore, rather doubtful according to present knowledge.

6. Störmer listed a *pre-Wenlock disturbance,* which resulted in the deposition of sandy beds in the Oslo area. According to Oftedahl the Lyngestein quartzite conglomerate may be Wenlockian, and the Ulven quartzite conglomerate may be related to the same event. Kulling (1972) suggested that the youngest conglomerates in the Swedish Caledonides, the Gimja and Aivo quartzite conglomerates, may be Wenlockian.

7. The late Silurian *Ardennian disturbance* has been generally considered to be the main Caledonian orogenic phase in Scandinavia (e. g. Vogt 1929). It has been supposed to involve downfolding of Cambro-silurian supracrustal rocks to great depths, deformation, metamorphism, migmatization, granitization and overthrusting.

Evidence obtained in recent years indicates that this opinion may have to be revised.

In Sweden Lower Silurian marine fossils are found in all nappes, except in the Uppermost Nappe (Kulling 1972) where no fossils are preserved. The youngest fossils are Lower Wenlockian, and it seems likely, that the thrusting of all nappes in that area was post Lower Wenlockian.

Evidence of the late or post Ardennian uplift is found in the sediments of the Oslo area. In the Upper Ludlow sand was transported from a large land mass to the north and west. The deposition continued throughout the Downtonian, when the whole of the Oslo area emerged above sea level.

If we use the Geological Time Table compiled by van Eysinga (1972), the post Ardennian land mass probably emerged between 10 and 15 million years after the deposition of the youngest marine fossiliferous beds of the Swedish nappes.

This time interval seems to be rather short for completion of the various activities which have been supposed to occur during the Ardennian phase. The age determinations presented in fig. 17 indicate, that intrusion of granitic rocks and major metamorphism at least in some parts of the Caledonides occurred during earlier phases, possibly the Ekne phase.

It seems likely, that the Ardennian phase, both in the Trondheim area and in the Swedish Caledonides, was mainly a phase of movement, and the importance of this phase as a phase of downfolding and metamorphism may have been overestimated.

As a conclusion it may be stated, that three of the seven disturbances in the Cambrian, Ordovician and Silurian periods seem to have been of major importance:

1. A Lower Ordovician phase involving intrusion and metamorphism (the Trondheim phase, about 490 m. y.).
2. An Upper Ordovician phase involving intrusion and metamorphism (the Ekne phase?, about 445 to 435 m. y.).
3. An upper Silurian phase involving large scale horizontal displacement and subsequent major uplift (the Ardennian phase about 415 to 405 m. y.).

Obviously more information is needed, especially in terms of carefully selected age determinations of Cambro-silurian rocks.

In East Greenland the main Caledonian orogeny according to Haller (1970) occurred 420–400 million years ago. The earlier view that the Ardennian phase was the most important phase in Scandinavia was in good agreement with this statement. The recent deformation discussed above indicates, however, considerable differences in the development of the Caledonides in Scandinavia and in East Greenland.

Metamorphism and movements

In recent years a large number of papers have been published presenting detailed studies of structures and metamorphism in minor areas of the Scandinavian Caledonides. In most papers four or five stages of deformation and metamorphism have been separated.

It would be of great interest to compile this large amount of detailed information, try to find whether a general picture of metamorphism and movements might be derived, and attempt to compare the results with information which can be obtained from other sources.

This task would, however, be outside the scope of this paper.

The general pattern of *Caledonian metamorphism* in Scandinavia is one of increasing metamorphism from east to west. Although there are exceptions, the main features may be summarized in the following way.

The foreland sediments are unmetamorphosed, but may locally have suffered mechanical deformation. Fossils are well preserved, and no intrusives occur.

The *miogeosynclinal* sediments exhibit low-grade metamorphism with sericite and chlorite in the eastern parts, biotite appearing in western parts, and with small garnets in some areas. Fossils are rarely preserved. Ultrabasic intrusives occur in the westernmost parts south of the Trondheim area, whereas in the Trondheim area they also occur in the eastern parts, possibly as the result of overthrusting.

The *eugeosynclinal rocks of eastern facies* vary greatly in their degree of metamorphism. Upper Ordovician and Lower Silurian fossils are found in several localities in the coastal areas of Western Norway and in the nappes of Northern Sweden. Middle and Lower Ordovician fossils are found only in the Trondheim area. The differences may be a result of varying regional intensity of the Lower Ordovician Trondheim disturbance, possibly also the Upper Ordovician Ekne disturbance.

The metamorphism varies from low greenschist facies to amphibolite facies with staurolite and kyanite. Basic and acid intrusions are numerous, but the Cambro-Silurian rocks do not seem to have been migmatized.

The *eugeosynclinal rocks* of the western facies are generally more metamorphosed than those of the eastern facies. Fossils have not been found, except at Smöla in the Trondheim area. (Whether Smöla belongs to the western facies may be questioned). Amphibolite facies metamorphism is widespread, as well as Caledonian migmatization, but in many places the relations between cover and basement are complex and it is difficult to decide whether the migmatized rocks are Cambro-Silurian or Precambrian. The great overthrust masses or nappes form an important element in the tectonic configuration of the Scandinavian Caledonides (fig. 18). During the first third of this century nappes were found mainly on the Swedish side of the border. Later they were found also in Norway, and now a considerable number of nappes have been found or postulated. Attempts have been made to compare nappe sequences in various parts of the Caledonides, but opinions are divided. Kulling (1972) separated five groups of nappes in Sweden. In Norway Strand (1972) inferred three groups of nappes and Oftedahl (1974) five.

As to the direction of movement of the nappes there is strong evidence of movement away from the central part of the orogen in the west towards the margin in the east.

Some authors have proposed that the uppermost nappe in Southern Norway, the Jotun Nappe, emerged from underneath its present position and spread like a mushroom to all sides during the Caledonian orogeny. This thesis is based upon the results of a gravity survey by Smithson (1964), but in the opinion of the present author the evidence is not convincing.

In East Greenland as well as in the northwest of Scotland the direction of overthrusting was towards the west or north-west. It seems clear, that on both sides of the orogen the movements were directed away from the central zone and transverse to the trend of the Caledonides.

Estimates of the *distance of movement* vary greatly. The lowermost nappes in Eastern Norway and in Sweden probably moved not more than a few tens of kilometers. For the higher nappes the distances were greater. Nappes in central Southern Norway moved more than 100 km above undisturbed Precambrian basement.

From the Trondheim area northward, movements of several hundred kilometers, even as much as 1000 km, have been postulated, but there is little reliable evidence for such estimates.

If Greenland and Scandinavia had the position indicated in fig. 3. when the thrusting began, translations of 400 to 500 km would place the roots of the nappes in the coastal areas of Greenland. As, however, both the folding and the overthrusting imply crustal

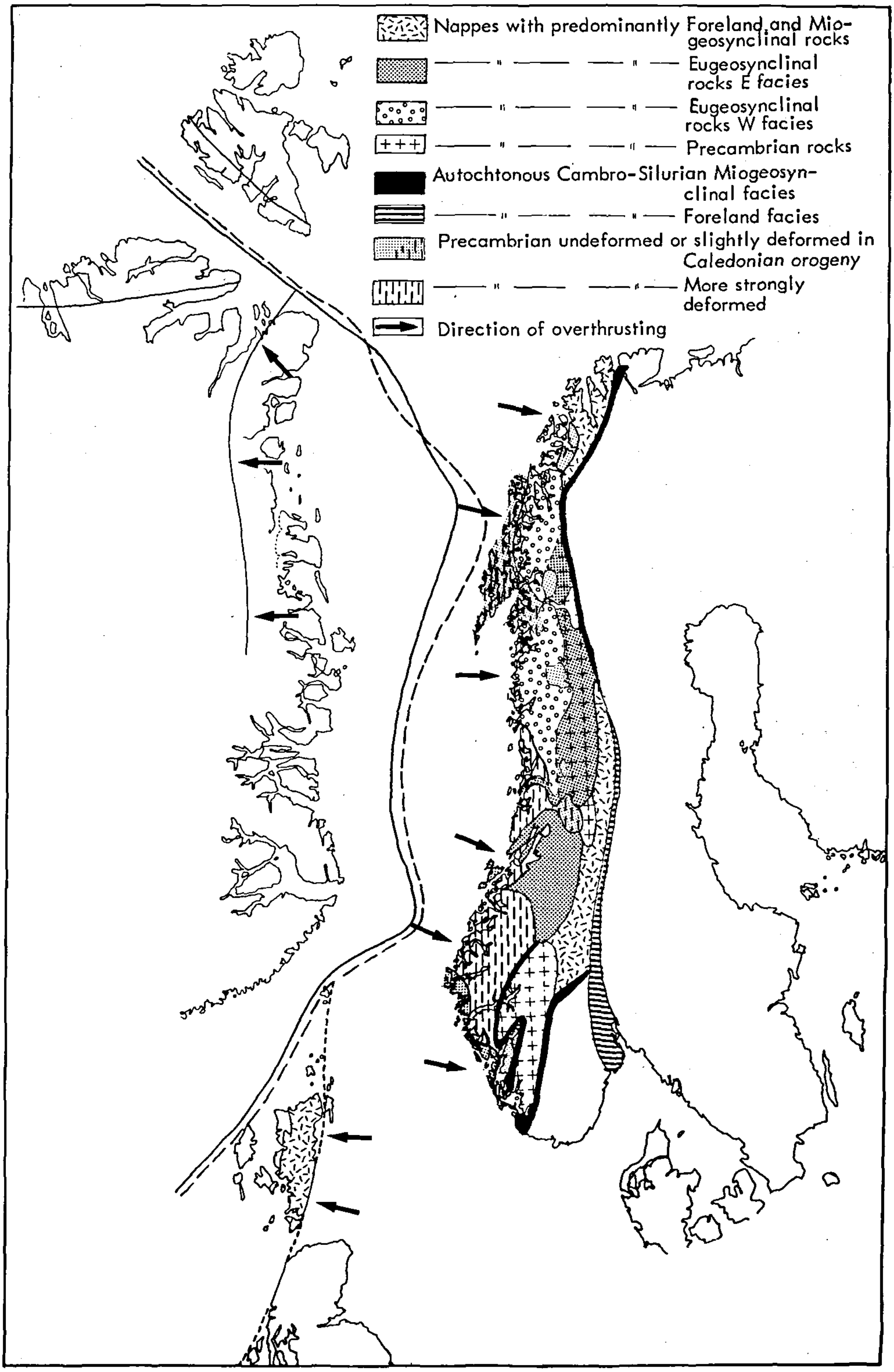


Fig. 18. Areas of nappes and directions of overthrusting in North-west Europe and East Greenland.

shortening, the continents must have been farther apart when the overthrusting began. Still it may be questioned if overthrusts exceeding 500 km as assumed by Gale & Roberts (1974) are feasible.

It is also pertinent to discuss the time-interval available for the overthrusting to have taken place. If the average horizontal displacement was 1 cm/year, 10 million years would be needed for a displacement of 100 km. This figure for horizontal displacement may be too small, but the problem should not be forgotten, when large overthrusts are postulated.

Attempts have been made to apply principles and models of plate tectonics to the Caledonides of Greenland and Scandinavia. Dewey & Bird (1970) envisaged a Benioff zone dipping westward underneath Greenland. Gale & Roberts (1972) and Ramsay (1973) have a Benioff zone dipping underneath Scandinavia. The author agrees with Ramsay (1973) that: "In the Norwegian Caledonides models of the evolving orogen in terms of a plate tectonic hyphothesis are still in the tentative and speculative stage."

Attempts have also been made (Gale & Roberts 1974) to separate the basic volcanics of the Norwegian Caledonides into tholeiitic and calc-alkaline types by using the Ti-Zr ratios (Pearce & Cann 1971, 1973). The results do not seem conclusive, and the author is not convinced, that enough is known about these ratios to make them reliable criteria for distinguishing between the two types of basalt in metamorphosed rocks.

There are characteristic differences between the various parts of the Scandinavian Caledonides with regards to the rocks involved in the overthrusting. From the Trondheim area northward rocks from all of the geosynclinal belts are found in the nappes, and the more westerly the belt, the higher the nappe.

The Trondheim area itself is now believed to contain one or more large nappes, but there is no indication that it has ever been overridden by higher tectonic units.

South of the Trondheim area the eugeosynclinal rocks occur only in the coastal area of Western Norway. At least in some areas they have moved eastward, but these movements seem to have been blocked by ridges of Precambrian basement.

East of these ridges we find in the Western and Central parts of Southern Norway that miogeosynclinal phyllites are overlain by nappes consisting of Precambrian and Eocambrian rocks. The highest tectonic unit is the Jotun Nappe, which, except in its basal parts, has been only slightly affected by Caledonian deformation and metamorphism, and where the Precambrian granulite facies assemblages are preserved to a great extent.

In Eastern Norway nappes of Eocambrian sparagmites lie below the Jotun Nappe.

In Western Norway the two Bergsdalen Nappes appear below the Jotun nappe. Both nappes wedge out to the northeast. In this area the tectonic units and their structures can be studied in great detail, due to a mountainous country and good outcrops. The interplay between the soft phyllite and the more resistant nappe rocks is clearly brought out by detailed mapping. Where the nappes become thicker, the phyllite between them is thinner. In areas of lower strain between the nappes, as at Voss, the phyllite may have an apparant thickness of more than 1000 m. A couple of kilometers away its thickness may be reduced to less than 10 m. In the Precambrian sediments of the Bergsdalen nappes primary structures are well preserved. But all secondary structures are related to Caledonian movements, even if corresponding rocks in the undisturbed Precambriam have been through two or three periods of Precambrian deformation. The Caledonian recrystallization and reorientation of minerals has been complete, in strong contrast to conditions in the overlying Jotun Nappe. The linear structures provide interesting information about the movement of the nappes, fig. 19. Their direction does not change at boundaries between different tectonic units. This may indicate, that when these structures were formed all tectonic units moved together.

Post-thrusting history

The sandstone deposits in the Oslo area tell of elevation of land masses to the north and west during the pre-Caradocian, the Horg (Taconic?) and the Wenlockian disturbances, at intervals of about 10 to 15 million years. All of

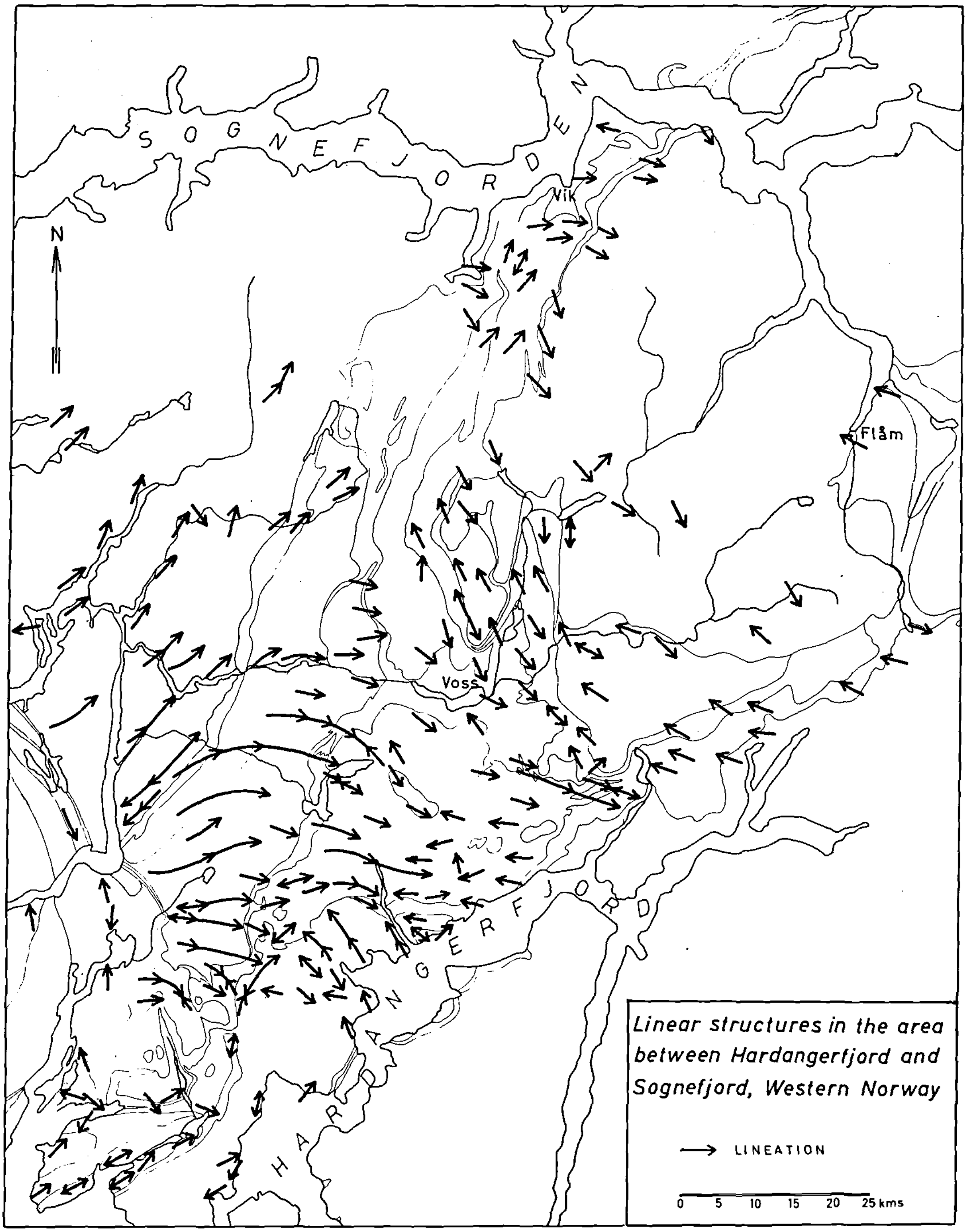


Fig. 19. Linear structures in the area between Hardangerfjord and Sognefjord, Western Norway.

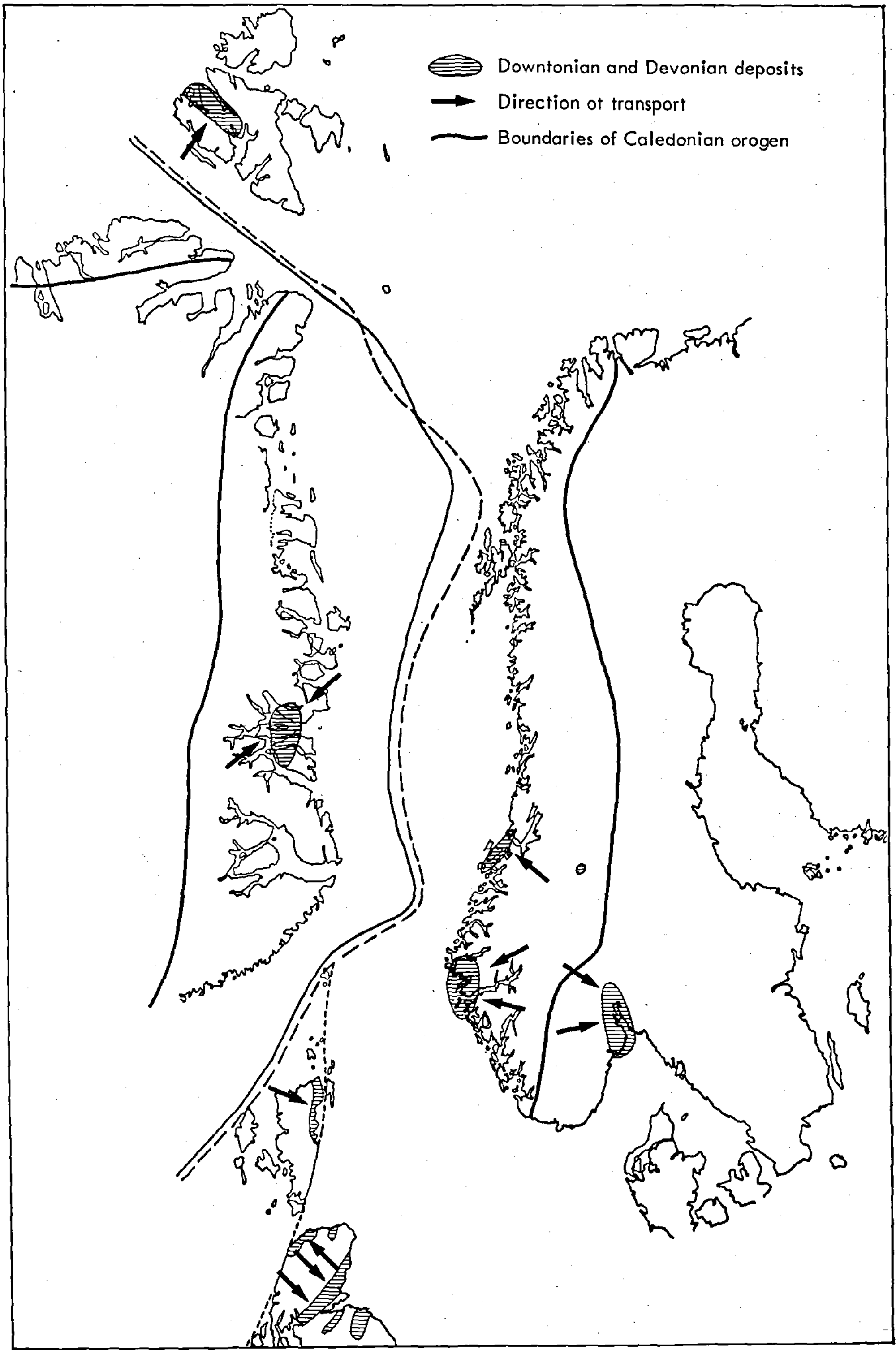


Fig. 20. Downtonian and Devonian continental deposits in North-west Europe and East Greenland.

these land masses were, however, only temporary areas of positive relief.

The post-Caledonian uplift which began in late Ludlowian time was on a different scale. During the Downtonian the entire Oslo area emerged above the sea, and more than 1000 m of sandstones of continental character with some shaly beds were deposited. Holtedahl (1953) assumed, that the folding which affected the Cambro-Silurian sediments of the Oslo area, including the Downtonian, occurred during the Erian disturbance.

Outside of the Oslo area post-Caledonian conglomerates and sandstones are found in three areas, fig. 20. Downtonian rocks occur west of Trondheim, Lower Devonian rocks occur south-east of Trondheim, and Middle Devonian rocks occur west and northwest of Trondheim and in the coastal areas north of Bergen.

The Middle Devonian rocks have a greater distribution than the older sediments, and it is clear, that they were deposited in separate intramontane basins at least some of which were limited by faults. All of the Devonian sediments in Norway are of continental character, and have a thickness of several thousand meters. In Western Norway the basal conglomerates in some areas lie on Precambrian gneisses. The latter during the Caledonian orogeny must have been deformed and metamorphosed at a depth of several kilometers.

The only evidence of volcanic activity in the Devonian of Norway is a zone of quartz keratophyre in the Solund area north of Bergen.

The Middle Devonian sediments in western Norway have been faulted, minor overthrusts occur, the rocks may be gently folded and in some places slightly metamorphosed. It has been assumed, that this happened during the pre-Upper Devonian orogenic phase which is called the Svalbardian phase, and which may have been contemporaneous with the Acadian phase.

The finding of oil in the North Sea has aroused new interest in the Devonian of Norway. Research is in progress, and in a few years our information about this period will, we hope, increase considerably.

Conclusion

This paper was originally read in honour of Professor J. Haller on the occasion of his receiving the Steno Medal of the Geological Society of Denmark. In conclusion it may be said, that although extensive research has been going on in the Caledonides of Scandinavia for many years, and although many general conclusions may be drawn from this work, it is evident that much more work is needed before we can present a picture of the Scandinavian Caledonides as clearly and as complete as that which Professor Haller has given of the development of the Caledonides in East Greenland.

Acknowledgement. Thanks are due to Brian A. Sturt for improving the English and for suggestions during preparation of the manuscript.

Norsk sammendrag

Artikkelen gir en oversikt over hovedtrekkene i de Skandinaviske kaledonider, og disse blir sammenlignet med kaledonidene på Öst-Grönland, under forutsetning av at de to kontinenter lå meget nærmere hverandre enn i dag. Grönlands posisjon i kaledonsk tid er antatt å være som foreslått av Bott og Watts (fig. 2), men er utarbeidet i detaljer på grunnlag av 500 m og 1000 dybdekurver på et kart av Eggvin et. al. Ved denne plassering vil imidlertid Vöringsplatået, som efter nyere undersökelser har mesozoiske og paleozoiske sedimenter og sannsynligvis en kontinental skorpe, nå 100 km vest for Grönlands nuværende kystlinje (fig. 6). Dette kan forklares enten ved at de to kontinenter hadde större avstand enn forutsatt (men likevel med parallel begrensning av den kontinentale skorpe), eller ved å anta en betydelig lateral forskyvning av Vöringplatået (fig 9). Den relative bevegelsesretning vil i så fall bli den samme som antatt for The Great Glen Fault og The Minch Fault. Begge disse forkastningslinjer ligger omtrent i fortsettelsen av bruddlinjer som skiller mellom kontinental og oseanisk skorpe utenfor Norges kyst.

Fig. 10 viser utbredelsen av senprekambriske og eokambriske sedimenter omkring det nordlige Atlanterhav. Forfatteren er skeptisk til den utbredte oppfatning at disse avleiringer representerer begynnelsen til den kaledonske geosynklinal.

I fig. 16 er vist den nuværende fordeling av de forskjellige geosynklinale fasies av kambro-siluriske bergarter i Nord-Europa og på Grönland. Kratonale sedimenter finnes i Sverige og i Östersjölandene. Mot vest kan skilles ut en sone av forlandssedimenter, en sone av miogeosynklinale avleiringer og to soner av eugeosynklinale avleiringer. Den östlige av disse har betydelige mengder av vulkanitter, spesielt basiske. Den vestlige sone har lite vulkanitter, men store mengder av kalksten og dolomitt. Suprakrustalbergarter tilhörende en vestlig miogeosynklinal sone er ikke påvist i Skandinavia, men bergartene i den vestlige eugeosynklinale sone viser likhetspunkter med dem på Spitsbergen og på Östgrönland. De sidste antas av Haller å være nærmest miogeosynklinale.

De orogene faser som har vært antatt for Skandinavia, Öst-Grönland og Storbritannia er sammenstillet i fig. 17. Der er også tatt med aldersbestemmelser av kaledonske bergarter i Skandinavia. Det er oppstillet ni orogene faser både i Storbritannia og i Skandinavia, men det er usikkert hvor mange av disse som har regional utbredelse. Det er også usikkert, i hvilken utstrekning de större faser er samtidige i hele området.

Efter en gjennomgåelse av de enkelte faser blir det antatt at tre faser er viktigere enn de andre:

1. En underordovicisk fase (Trondheim-fasen) for ca. 490 mill. år siden, med intrusjon og metamorfose.
2. En overordovicisk fase for ca. 445 til 435 mill. år siden (Eknefasen), med intrusjon og metamorfose.
3. En oversilurisk fase (den Ardenniske fase) for ca. 415 til 405 mill. år siden med store horisontale bevegelser, spesielt overskyvninger, og efterfölgende landhevning.

Til tross for at adskillige arbeider fra de senere år beskriver faser av deformasjon og metamorfose i mindre områder av de skandinaviske kaledonider, er det ennu vanskelig å forbinde disse til et helhetsbilde og å sette dette i relasjon til de orogene faser som er oppstillet. Det er likevel en klar forskjell i graden av metamorfose av de forskjellige geosynklinale soner.

Forlandssedimentene er i alminnnelighet umetamorfosert, men de har lokalt vært utsatt for mekanisk metamorfose. Fossiler er godt bevart, og intrusiver mangler.

De miogeosynklinale sedimenter har lav metamorfosegrad. I öst opptrer sericitt og kloritt, i vest biotitt, lokalt med små granater. Ultrabasiske intrusiver opptrer i vest. Fossiler er bevart i enkelte områder i öst.

De eugeosynklinale bergarter av östlig fasies varierer meget i metamorfosegrad. Fossiler fra undre Ordovicium til undre Silur finnes i enkelte lokaliteter. Metamorfosegraden varierer fra lav grönnskiferfasies til amfibolittfasies. Basiske og sure instrusiver opptrer i adskillig utstrekning.

De eugeosynklinale bergarter av vestlig fasies er mer metamorfosert. Fossiler mangler, amfibolittfasies er vanlig, og migmatisering forekommer.

Et stort antall skyvedekker er påvist i de skandinaviske kaledonider, men det er usikkert hvorledes de skal kombineres til större enheter. Alle dekker er skjövet tvers på fjellkjedens lengderetning, de fleste mellom ESE og SSE. Skyvedistansene synes å være minst i de laveste dekker, i de höyere dekker kan den bli mer enn 100 km, muligens flere hundre km.

I Öst-Grönland og i Skotland har overskyvninger også foregått tvers på fjellkjedens lengderetning, men her har bevegelsen gått mot vest.

Den post-kaledonske hevning kan i Oslo-feltet registreres fra övre Ludlow, og kontinentale sedimenter finnes i Syd-Norge fra Downton, fra undre og fra midtre Devon, sannsynligvis avsatt i intramontane bekkener. De mellomdevonske sedimenter i Vest-Norge kan være adskillige tusen meter mektige, og de er tildels avsatt på prekambriske bergarter, som under den kaledonske fjellkjedefoldning har vært metamorfosert på adskillige kilometers dyp.

De devonske bergarter kan være foldet i åpne folder, de er tildels forkastet, og mindre overskyvninger opptrer. Lokalt kan de ha spor av svak metamorfose. Bevegelsene antas å ha foregått i den Svalbardiske (Acadiske?) fase för övre Devon.

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