MEDDELELSER OM GRØNLAND

UDGIVNE AF

KOMMISSIONEN FOR VIDENSKABELIGE UNDERSØGELSER I GRØNLAND

Bd. 206 · Nr. 6

DEVONIAN SEDIMENTS OF EAST GREENLAND VI

REVIEW OF RESULTS

BY

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WITH 34 FIGURES

Nyt Nordisk Forlag Arnold Busck

København 1983

Abstract

Seventy generalised stratigraphical columns, and alphabetical and hierarchical indexes of the lithostratigraphical units, are used to summarise stratigraphical relationships. The total aggregate thickness is 10 400 m, adding the maximum thicknesses of each of the five major units. Vertebrate fossils indicate an age range from Upper Middle Devonian (Givetian) to highest Devonian or lowest Carboniferous (Famennian or Tournaisian). A palynological survey has yielded two good micro-floral assemblages, one of Middle to Upper Givetian age, and the other of late Frasnian or early Famennian age, and both of these are consistent with the vertebrate evidence. Conglomerate, sandstone, siltstone and volcanic rock lithological associations are reviewed, and provide detailed evidence of local processes and environments. Some of the most original information concerns the three-dimensional patterns of major sedimentary rock bodies, representing different environmental situations.

Folds, faults and unconformities in the Devonian rocks are reviewed, and define a sequence of (i) early movements, (ii) Kap Franklin Deformation, (iii) Hudson Land Deformation, and (iv) Ymer Ø phase. The structural and sedimentary data are assembled onto ten "unit" maps, representing different time episodes. Most of the major events in the sequence of these episodes appear to be tectonically controlled, but both the major sedimentary basins (Vilddal and Gauss) show gross fining-upwards trends that may have been climatically controlled.

The tectonic controls may have been the activity of a number of northerly trending major fracture zones. These were zones of differential vertical and horizontal (strike-slip) movement, volcanism and granite emplacement. Major zones of this sort appear to have been characteristic of the continent-continent collision that occurred in Devonian times in many parts of the Caledonides.

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ISBN 87-17-02975-9
ISSN 0025-6676
BIANCO LUNOS BOGTRYKKERI A/S

Contents

INTRODUCTION

In this paper we review our work on the Devonian sediments of East Greenland, and present some general conclusions.

Previous numbers of this volume have provided much of the detail. These numbers are

Number 1: Introduction, classification of sequences, petrographic notes (FRIEND, ALEXANDER-MARRACK, NICHOLSON & YEATS, 1976a)
Number 2: Sedimentary structures and fossils (FRIEND, ALEXANDER-MARRACK, NICHOLSON & YEATS, 1976b)
Number 3: The Eastern Sequence, Vilddal Supergroup and part of the Kap Kolthoff Supergroup (ALEXANDER-MARRACK & FRIEND, 1976)
Number 4: The Western Sequence, Kap Kolthoff Supergroup of the western areas (YEATS & FRIEND, 1978)
Number 5: The Central Sequence, Kap Graah Group and Mount Celsius Supergroup (NICHOLSON & FRIEND, 1976)

In this present number, written largely by P. F. FRIEND, our object is to bring this work together, and examine it in the light of latest thinking. We hope to pick out aspects of the sedimentation, and its control, that are of most general interest. We also include, for the first time, stratigraphical detail of the palynological work carried out by one of us (K. C. ALLEN).

REVIEW OF STRATIGRAPHIC RELATIONS

Figs 1 and 2 review the age and location of the major stratigraphic units that we have distinguished. Our detailed knowledge of stratigraphic (lithostratigraphic) relations is presented in a series of columns (Figs 3–11), representing successions throughout the outcrop area and located on three maps (Figs 12–14). In these columns we have distinguished the main sediment associations (conglomerate; sandstone – medium or fine; siltstone), and we shall be discussing the interpretation of these associations further below.

To allow easier synthesis, we have divided up the complete package of Devonian stratigraphic units into ten informal numbered units. Going from oldest to youngest, these units correspond to the major stratigraphic units as shown below.

Informal unit 1, pre Vilddal rocks
– – 2, lower Vilddal Supergroup
– – 3, upper Vilddal Supergroup
– – 4, lower Kap Kolthoff Supergroup
– – 5, middle Kap Kolthoff Supergroup
– – 6, upper Kap Kolthoff Supergroup
– – 7, lower Kap Graah Group
– – 8, upper Kap Graah Group
– – 9, lower Mount Celsius Supergroup
– – 10, upper Mount Celsius Supergroup

Table 1 shows the arrangement of the stratigraphic units into their hierarchies.

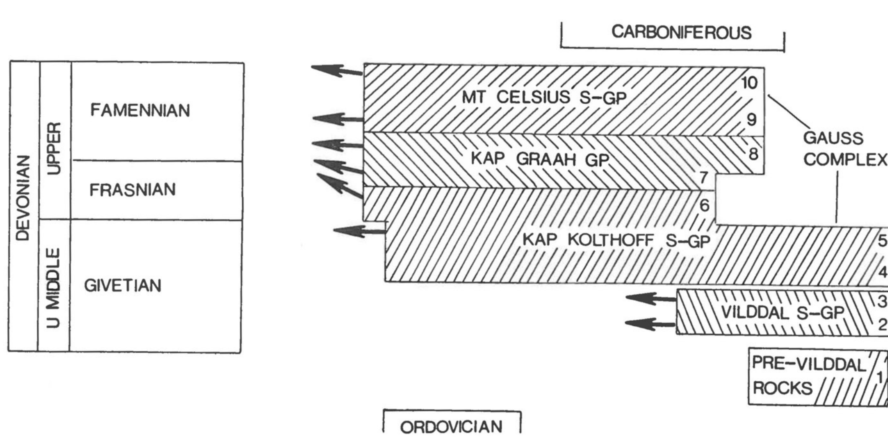

Fig. 1. Summary chart showing the ages and mutual relationships of the major stratigraphic units, and the informal numbered units used in this paper.

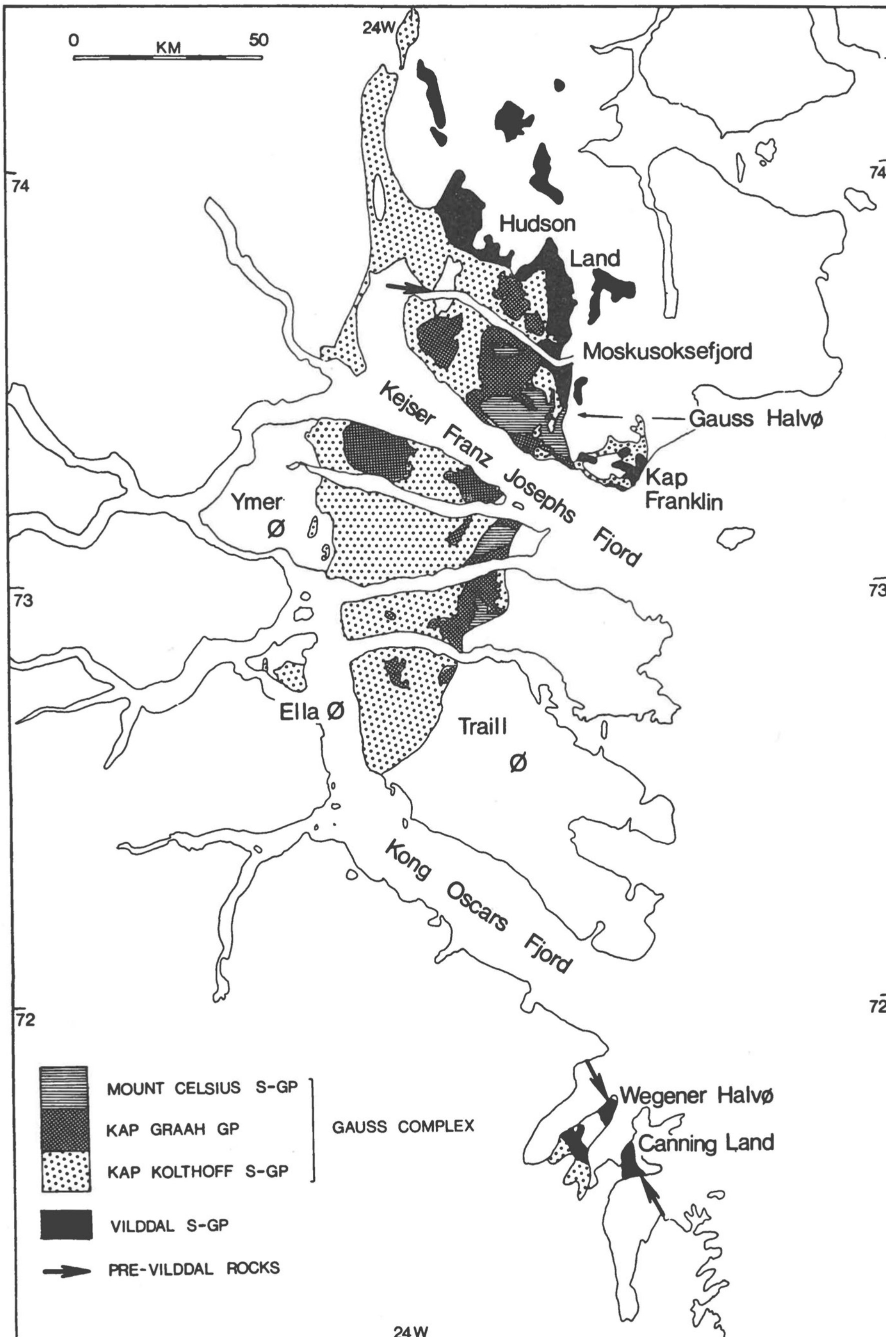

Fig. 2. Summary geological map of Devonian strata of East Greenland, showing the five major stratigraphic units.

ALPHABETICAL LISTING (LEXICON) AND BRIEF DESCRIPTION OF STRATIGRAPHIC UNITS

In this section we list all the stratigraphic units for which we have used formal names, and some of the older terms (with inverted commas) that have been replaced. In many cases, particularly in the Kap Kolthoff Supergroup and Kap Graah Group, we have used names for local descriptions, but not considered it desirable to formalise the units.

All our units are rock stratigraphic (lithostratigraphic), and we have used the generally accepted terms and methods of naming (HARLAND, 1972; HEDBERG, 1976).

For each unit we shall list, in order:

1) Reference publication
2) Higher order stratigraphic units
3) Locality number (Figs 12–14)
4) Abbreviation (Figs 3–11)
5) Informal numbered unit
6) Brief description of lithology
7) Estimate of thickness
8) Nature of bottom and top boundary

Aina Dal Formation. NICHOLSON & FRIEND (1976), Mount Celsius Supergroup, Remigolepis Group. Location 66 (AD), unit 4. Red coarse and medium grained siltstones. Up to 80 m thick. Transition below from Kap Graah Group. Transition above to Wimans Bjerg Formation.

"*Asterolepis Series*". SÄVE-SÖDERBERGH (1937), corresponds to our Vimmelskaftet Red Siltstone Member.

"*Basal Series*". BÜTLER (1959). Replaced term for the western marginal sediments, classified by us as Kap Kolthoff Supergroup, Inlier Konglomerat 1, and some of the Vilddal Supergroup of Hudson Land and Gauss Halvø.

Basisdalen Conglomerate. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nathorst Fjord Group. Locality 6 (BC), unit 2. Conglomerate of volcanic rocks and Eleonore Bay Group quartzites. Up to 70 m thick. Unconformity below; transition above to South Hesteskoen Formation.

Britta Dal Formation. NICHOLSON & FRIEND (1976), Mount Celsius Supergroup, Remigolepis Group. Locality 66 (BD), unit 9. Red and grey siltstones and subsidiary red sandstones. Up to 550 m thick. Transition below from Wimans Bjerg Formation; transition above to Grønlandaspis Group.

East Ramsays Bjerg Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Ramsays Bjerg Group. Locality 4 (ERBS), unit 2. Grey fine grained sandstones with red and grey siltstones. 500 m thick. Base not exposed; transition above to West Ramsays Bjerg Conglomerate.

Ella Ø Conglomerate Member. YEATS & FRIEND (1978), Kap Kolthoff Supergroup, Lower Rødebjerg Formation. Locality 33 (EOC), unit 5. Conglomerates, mainly with limestone clasts, with subordinate siltstone and limestone units near the base. 1000 m thick. Unconformity below; upper boundary not exposed.

"*Franz Joseph Complex*", FRIEND (1978). Name now replaced by Gauss Complex, because name "Franz Joseph Beds" used by WORDIE (1927) for Eleonore Bay and Tillite Groups and Lower Palaeozoic strata.

Gauss Complex. New name introduced here to include Kap Kolthoff Supergroup, Kap Graah Group and Mount Celsius Supergroup. Name replaces Franz Joseph Complex of FRIEND (1978). Complex covers units 4 to 10. Red, green and grey conglomerates, sandstones and siltstones with local volcanic rocks. Unconformity below, on Vilddal Supergroup and older rocks. Upper boundary always erosional.

Giesecke Bjerge Group. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup, includes Kap Franklin and Randbøl Formations. Locality 25 (LV, SB, UV, DGS, RB), units 4 and 5. Volcanic rocks (mainly tuffs and felsites), sandstones and conglomerates. Up to 900 m for Kap Franklin Formation and 900 m for Randbøl Formation. Unconformity below and above.

Grønlandaspis Group. NICHOLSON & FRIEND (1976), Mount Celsius Supergroup. Locality 64 (GG), unit 10. Grey fine and medium grained sandstones with minor conglomerate and shale units. Up to 600 m thick. Transitional below from Remigolepis Group; upper boundary not exposed.

"*Gyroptychius groenlandicus Series*". SÄVE-SÖDERBERGH (1937), fourth division. Corresponds to our Vimmelskaftet Red-and-green banded Siltstone Member.

"*Heterostius Series*". SÄVE-SÖDERBERGH (1937). Corresponds to our South Hesteskoen Formation.

Hjelmbjergene Group. ALEXANDER-MARRACK & FRIEND (1976), NICHOLSON & FRIEND (1976), Kap Kolthoff Supergroup, includes Grey Sandstone, Red and Grey Banded Sandstone, and Red Sandstone Formations. Locality 23 (HG, HRG, HR), units 5 and 6. Grey and red medium and fine grained sandstone. Up to 2500 m thick. Basal boundary not exposed; upper boundary not exposed.

Hjelmbjergene Grey Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup, Hjelbjergene Group. Locality 23 (HG), unit 5. Grey coarse, medium and fine grained sandstones. 1100 m thick. Basal boundary not exposed; upper boundary faulted out.

Hjelmbjergene Red and Grey Banded Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup, Hjelmbjergene Group. Locality 23 (HRG), unit 5(?). Grey sandstones with red medium and fine grained sandstone and siltstones. Up to 600 m thick. Basal boundary faulted; upper boundary faulted.

Hjelmbjergene Red Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup, Hjelmbjergene Group. Locality 23 (HR), unit 6. Red fine, medium and coarse grained sandstones. 800 m thick. Basal boundary faulted; unconformity above.

Inderdalen Formation. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Vilddal Group. Exposed in Margrethedal, east of the Kap Franklin area (locality 5), units 2 and 3. Grey siltstones passing upwards into red and green banded siltstones. Several hundred metres thick. Base not exposed; top is unconformity below Rødedal Formation.

Inlier Konglomerat 1. BÜTLER (1959, p. 39), pre-Vilddal rocks, locality 1 (Kongl. 1), unit 1. Conglomerate, mainly of limestone clasts, with minor red fine sandstone. 180 m thick. Base and top unconformable.

Inlier Konglomerat 2. BÜTLER (1959, p. 39), Vilddal Supergroup. Locality 1 (Kongl. 2), unit 2. Conglomerate of granite and vein quartz clasts, with red fine grained sandstones. 1000 m thick. Base and top unconformable.

Kap Fletcher Formation. ALEXANDER-MARRACK & FRIEND (1976), CABY (1972) pre-Vilddal rocks, locality 6 (KF), unit 1. A thin basal conglomerate followed by tuffs and lavas (mainly rhyodacites and latites). About 1000 m thick. Conglomerate suggests unconformity at base; unconformity at top.

Kap Franklin Formation. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup, Giesecke Bjerg Group. Locality 25 (LV–OGS), unit 4. Lavas and tuffs with sandstones and conglomerates. Up to 900 m thick. Basal and upper contacts unconformable.

Kap Franklin Lower Volcanic Member. ALEXANDER-MARRACK & FRIEND (1976), Kap Franklin Formation. Locality 25 (LV), unit 4. Felsitic Lavas. Up to 360 m thick. Basal contact unconformable; upper contact with Saxos Bjerg Member.

Kap Franklin Østreplateau Grey Sandstone Member. ALEXANDER-MARRACK & FRIEND (1976), Kap Franklin Formation. Locality 25 (OGS), unit 4. Grey fine grained sandstones. Up to 350 m thick. Basal contact with Upper Volcanic Member; upper boundary is unconformity.

Kap Franklin Saxos Bjerg Member. ALEXANDER-MARRACK & FRIEND (1976), Kap Franklin Formation. Locality 25 (SB), unit 4. Grey fine sandstones. Up to 350 m thick. Basal contact with lower Volcanic Member; upper boundary is unconformity.

Kap Franklin Upper Volcanic Member. ALEXANDER-MARRACK & FRIEND (1976), Kap Franklin Formation. Locality 25 (UV), unit 4. Lavas (mainly rhyolites) and pyroclastic rocks. Up to 340 m thick. Basal contact with Saxos Bjerg Member; upper contact with Østreplateau Grey Sandstone Member.

Kap Graah Group. NICHOLSON & FRIEND (1976). Localities 42–63 (KG), units 7 and 8. Red and grey sandstones with subsidiary amount of siltstone and volcanic rocks. Up to 1700 m thick. Base generally conformable on Kap Kolthoff Supergroup, but locally an unconformity; upper boundary transitional into Mount Celsius Supergroup.

Kap Kolthoff Supergroup. ALEXANDER-MARRACK & FRIEND (1976), YEATS & FRIEND (1978), includes Hjelmbjergene and Giesecke Bjerge Groups and the Upper Rødebjerg, Lower Rødebjerg, Sederholms Bjerg Grey Sandstone, Sofia Sund, Quensel Bjerg and Langbjerg Red Sandstone Formations. Localities 7–41 (KK), units 4–6. Grey and red sandstones with local conglomerates and volcanic rocks, Thickness up to 3000 m, and possibly as much as 6500 m in Strindbergs Land. Unconformable base; upper boundary is a generally conformable contact with the Kap Graah Group.

Karins Dal Grey Siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Ramsays Bjerg Group. Locality 4 (KGS), unit 2. Grey siltstones, 400 m thick. Transition from West Ramsays Bjerg Conglomerate below; faulted contact with Ramsays Bjerg Red-and-green banded Siltstone above.

Langbjerg Red Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup. Locality 15 (LR), unit 6. Red medium and fine grained sandstones About 500 m thick. Base disconformable; top unconformable.

Lower Rødebjerg Formation. YEATS & FRIEND (1978), Kap Kolthoff Supergroup. Locality 28 (LR), unit 5. Red and grey sandstones with major local conglomerates (e.g. Ella Ø Conglomerate Member). Up to 1000 m thick. Unconformity where base is exposed; upper contact transitional into Upper Rødebjerg Formation.

"*Lower Sandstone Complex*". Replaced term. First used by SÄVE-SÖDERBERGH (1933) for strata below the Remigolepis Group of Gauss Halvø. Later used by JARVIK (1961) for strata below "Phyllolepis Series" (Kap Graah Group).

Mount Celsius Supergroup. NICHOLSON & FRIEND (1976), includes Remigolepis end Grønlandaspis Groups. Locality 64 (MC, RG and GG), units 9 and 10. Red and grey siltstones succeeded by grey sandstones. Up to 1200 m thick. Transition below from Kap Graah Group; upper boundary erosional.

Nathorst Fjord Group. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, includes West Hesteskoen, Vimmelskaftet and South Hesteskoen Formations and Basisdalen Conglomerate. Locality 6, (BC–WHF), units 2 and 3. Grey, red-and-grey and red siltstones, sandstones and a basal conglomerate. 1550 m thick. Base and top unconformable.

Nordhoeksbjerg Conglomerate. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nordhoeksbjerg Group. Locality 3 (NC), unit 2. Conglomerate of limestone and quartzite clasts. 300 m thick. Basal contact unconformable; upper boundary transitional to Nordhoeksbjerg Mixed Sandstone-and-siltstone.

Nordhoeksbjerg Green Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nordhoeksbjerg Group. Locality 3 (NGS), unit 2. Grey medium and fine grained sandstones. 300 m thick. Base transitional from Nordhoeksbjerg Mixed Sandstone-and-siltstone Formation; transition above to Nordhoeksbjerg Red-and-green banded Siltstone Formation.

Nordhoeksbjerg Group. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, includes Nordhoeksbjerg Conglomerate, Mixed Sandstone-and-siltstone, Green Sandstone and Red-and-grey banded Siltstone Formations. Locality 3 (NC–NRS), units 2 and 3. Grey and red siltstones and sandstones, with major basal conglomerate. Up to 2200 m thick. Base and top unconformable.

Nordhoeksbjerg Mixed Sandstone-and-siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nordhoeksbjerg Group. Locality 3 (NS), unit 2. Alternations of grey mediu mgrained sandstones and red siltstones and fine grained sandstones. 100 m thick. Transition below from Nordhoeksbjerg Conglomerate; transition above to Nordhoeksbjerg Green Sandstone.

Nordhoeksbjerg Red-and-green banded Siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nordhoeksbjerg Group. Locality 3 (NRS), unit 3. Red and green siltstones. Up to 1500 m thick. Transition below from Nordhoeksbjerg Green Sandstone; top unconformable.

"*Plant-bearing Series*". SÄVE-SÖDERBERGH (1937), division 3. Replaced term, equivalent to our Vimmelskaftet Grey Sandstone Member.

"*Phyllolepis Series*". SÄVE-SÖDERBERGH (1937). Replaced term. Equivalent to pre Remigolepis Group strata in Gauss Halvø, or (Phyllolepis Schichten) to include Remigolepis Group and Kap Graah Group (BÜTLER, 1959, inserted table).

Pre-Vilddal rocks. Informal term used here to include Kap Fletcher Formation, and Inlier Konglomerat 1. Localities 6 and 1, unit 1. Volcanic rocks and conglomerates. Unconformable base and top.

Quensel Bjerg Formation. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup. Locality 41, unit 6. Grey, pink and yellow, coarse to fine grained sandstones and conglomerates. 300 m thick. Base unconformable, top unconformable.

Ramsays Bjerg Group. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, includes East Ramsays Bjerg Sandstone, West Ramsays Bjerg Conglomerate, Karins Dal Grey Siltstone and Ramsays Bjerg Red-and-green banded Siltstone. Locality 4 (ERBS–RBRS), units 2 and 3. Sandstones, siltstones and conglomerates. 2600 m thick. Base not exposed; top unconformable.

Ramsays Bjerg Red-and-green banded Siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Ramsays Bjerg Group. Locality 4 (RBRS), unit 3.

Red and green siltstone. Up to 1500 m thick. Transition below from Karins Dal Grey Siltstone; top unconformable.

"Ramsays Bjerg Series". Replaced term. Used by BÜTLER (1959) for a variety of units along the western edge of the Devonian outcrop area (included by us in the Ramsays Bjerg Group), and beside the 'inlier' in western Moskusoksefjord (included by us in Inlier Konglomerat 2).

Randbøl Formation. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup, Giesecke Bjerge Group. Locality 25 (RB), unit 5. Conglomerates and yellow, white and reddish coarse to medium grained sandstones. Up to 900 m thick. Unconformable base and top.

Remigolepis Group. NICHOLSON & FRIEND (1976). Mount Celsius Supergroup, includes Aina Dal, Wimans Bjerg and Britta Dal Formations. Locality 64 (RG), unit 9. Red and grey siltstones with subordinate sandstones. Up to 830 m thick. Transition below from Kap Graah Group; transition above to Grønlandaspis Group.

Rødedal Formation. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup. Locality 24 (RD), unit 4. Conglomerates, tuffs and sandstones. Up to 200 m thick. Unconformable base and top.

Sederholms Bjerg Grey Sandstone. ALEXANDER-MARRACK & FRIEND (1976), Kap Kolthoff Supergroup. Locality 15 (SBGS), unit 6. Grey medium grained sandstones. Up to 100 m thick. Unconformable base; transition above to Langbjerg Red Sandstone.

Sofia Sund Formation. YEATS & FRIEND (1978), Kap Kolthoff Supergroup. Locality 6 (SS), unit 6. Grey sandstones with minor red sandstones. Up to 1400 m thick. Transition below from Upper Rødebjerg Formation; transition above to Kap Graah Group.

South Hesteskoen Formation. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nathorst Fjord Group. Locality 6 (SHF), unit 2. Grey and red sandstones and siltstones. Up to 50 m thick. Transition below from Basisdalen Conglomerate; transition above to Vimmelskaftet Formation.

Upper Rødebjerg Formation. YEATS & FRIEND (1978), Kap Kolthoff Supergroup. Locality 28 (UR), unit 5. Medium and fine grained sandstones, mainly red. Up to 1000 m thick. Transition below from Lower Rødebjerg Formation; transition above to Sofia Sund Formation.

Vilddal Grey Siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Vilddal Group. Locality 5 (VGS), unit 2. Grey siltstones. Up to 400 m thick. Transition below from Vilddal Pebbly Sandstone and Siltstone; transition above to Vilddal Red and Green Banded Siltstone.

Vilddal Group. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, includes pebbly sandstone and Siltstone, Grey Siltstone, Red-and-green banded Siltstone and the Inderdalen Formation. Locality 5 (VPS–VRGS), units 2 and 3. Grey and red siltstones, with pebbly sandstones low in the succession. Up to 1350 m thick. No base exposed; unconformable top.

Vilddal Pebbly Sandstone and Siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Vilddal Group. Locality 5 (VPS), unit 2. Grey coarse and medium grained sandstones alternating with grey siltstones. 200 m thick. No base exposed; transition above to Vilddal Grey Siltstone.

Vilddal Red-and-green banded Siltstone. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Vilddal Group. Locality 5 (VRGS), unit 3. Red and grey siltstones. 750 m thick. Transition below from Vilddal Grey Siltstone; top unconformable.

Vilddal Supergroups. ALEXANDER-MARRACK & FRIEND (1976). Locality 5 (VPS–

VRGS), units 2 and 3. Grey and red siltstone with sandstone and conglomerate. Up to 2600 m thick. No base exposed, unconformable top.

Vimmelskaftet Formation. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nathorst Fjord Group, includes Red Siltstone, Grey Sandstone and Red-and-green banded Siltstone Members. Locality 6 (VRSM–VRGSM), units 2 and 3. Red and green siltstones with sandstones. 1400 m thick. Transition below from South Hesteskoen Formation; transition above to West Hesteskoen Formation.

Vimmelskaftet Grey Sandstone Member. ALEXANDER-MARRACK & FRIEND (1976), Vimmelskaftet Formation. Locality 6 (VGSM), unit 3. Grey medium and fine grained sandstones, locally with red siltstone. Average 550 m thick. Transition below from Vimmelskaftet Red Siltstone Member; transition above to Red-and-green banded Siltstone member.

Vimmelskaftet Red-and-green banded Siltstone Member. ALEXANDER-MARRACK & FRIEND (1976), Vimmelskaftet Formation. Locality 6 (VRGSM), unit 3. Red and green siltstones. Average 450 m thick. Base transitional from Vimmelskaftet grey sandstone member; top concordant boundary with West Hesteskoen Formation.

Vimmelskaftet Red Siltstone Member. ALEXANDER-MARRACK & FRIEND (1976), Vimmelskaftet Formation. Locality 6 (VRSM), unit 2. Red siltstone. 400 m thick. Basal boundary South Hesteskoen Formation; top boundary with Vimmelskaftet Grey Sandstone Member.

West Hesteskoen Formation. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Nathorst Fjord Group. Locality 6 (WHF), unit 3. Conglomerate overlain by red and yellow coarse sandstones. 50 m thick. Basal concordant boundary with Vimmelskaftet Formation; top unconformable.

West Ramsays Bjerg Conglomerate. ALEXANDER-MARRACK & FRIEND (1976), Vilddal Supergroup, Ramsays Bjerg Group. Locality 4 (WRBC), unit 2. Conglomerate overlain by red and grey sandstones with siltstones. 200 m thick. Basal boundary with East Ramsays Bjerg Sandstone; top boundary with Karins Dal Grey Siltstone.

Wimans Bjerg Formation. NICHOLSON & FRIEND (1976), Mount Celsius Supergroup, Remigolepis Group. Locality 66 (WB), unit 9. Grey siltstones. Up to 200 m thick. Transition below from Aina Dal Formation; transition above to Britta Dal Formation.

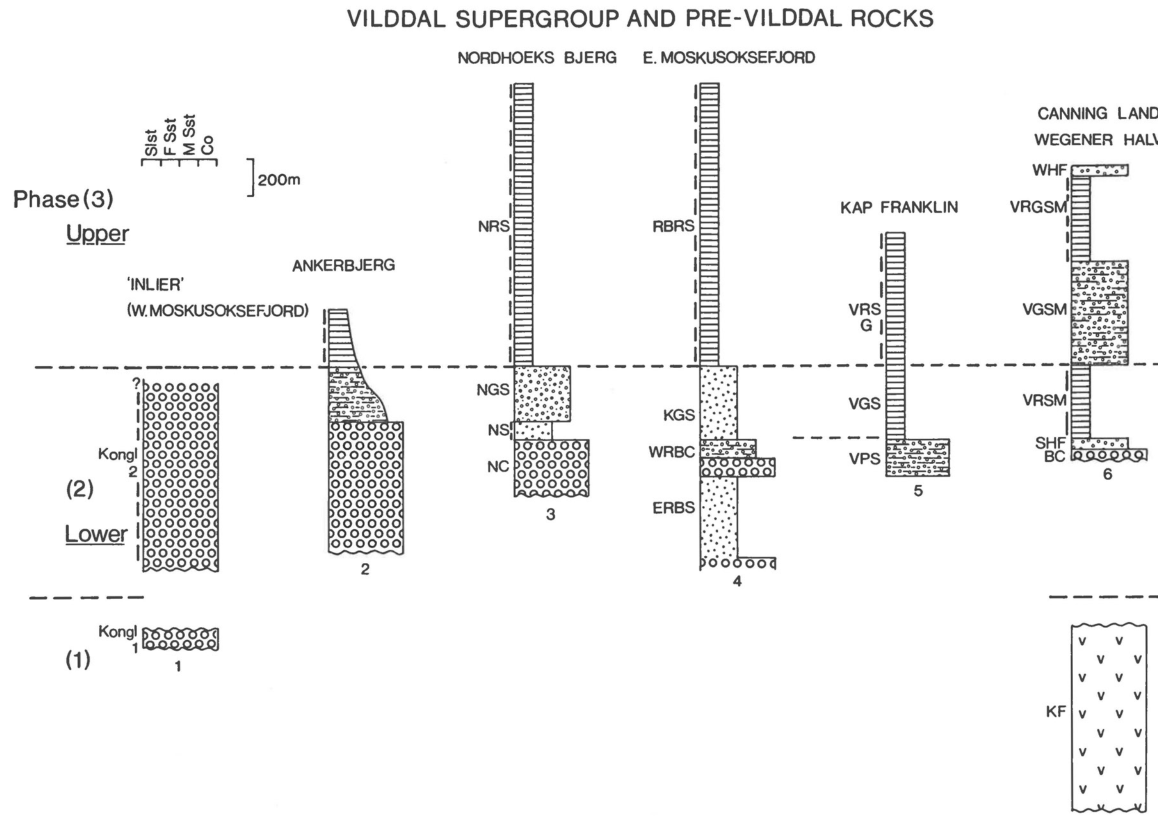

Fig. 3. Summary stratigraphic columns in the Vilddal Supergroup and pre-Vilddal Rocks. Numbers below each column refer to localities on Fig. 12. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). Red sediments are shown by an extra line on the left margin of a column. A, aeolian; V, volcanic.

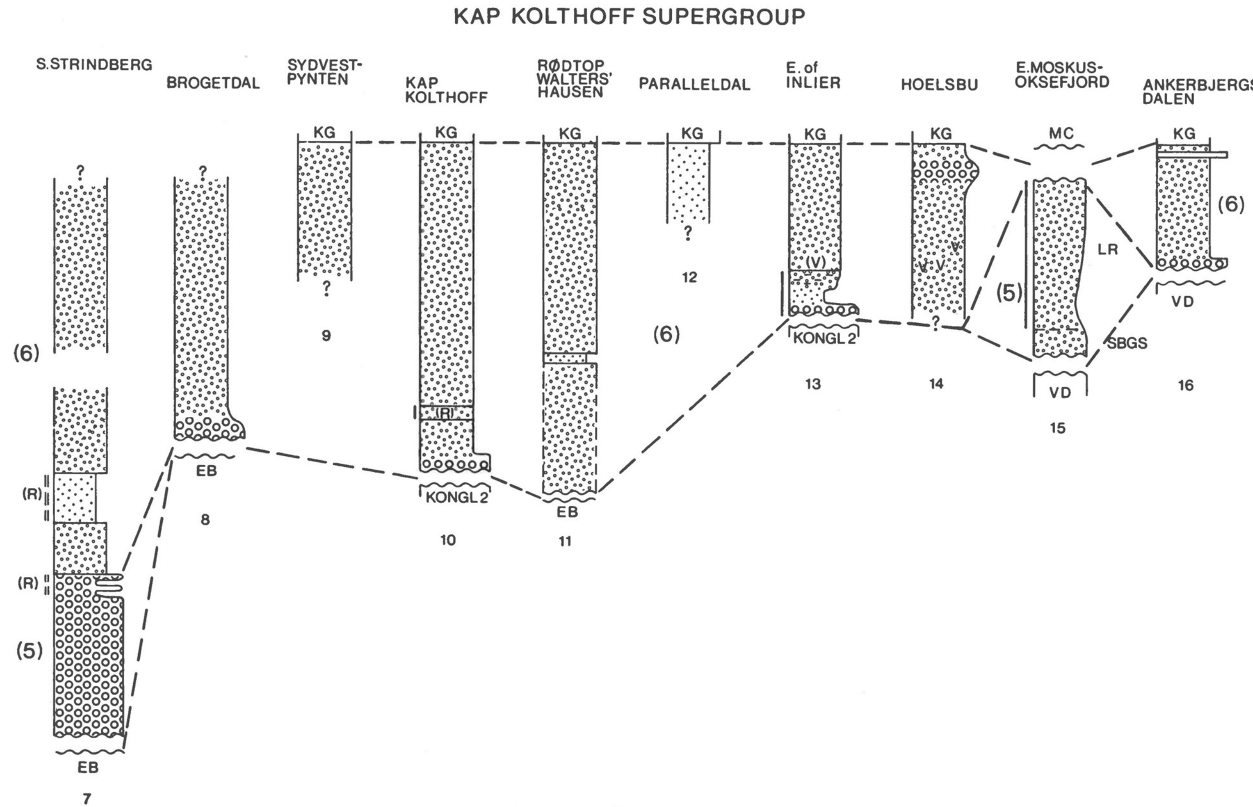

Fig. 4. Summary stratigraphic columns in the Kap Kolthoff Supergroup. Numbers below each column refer to localities in Fig. 13. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

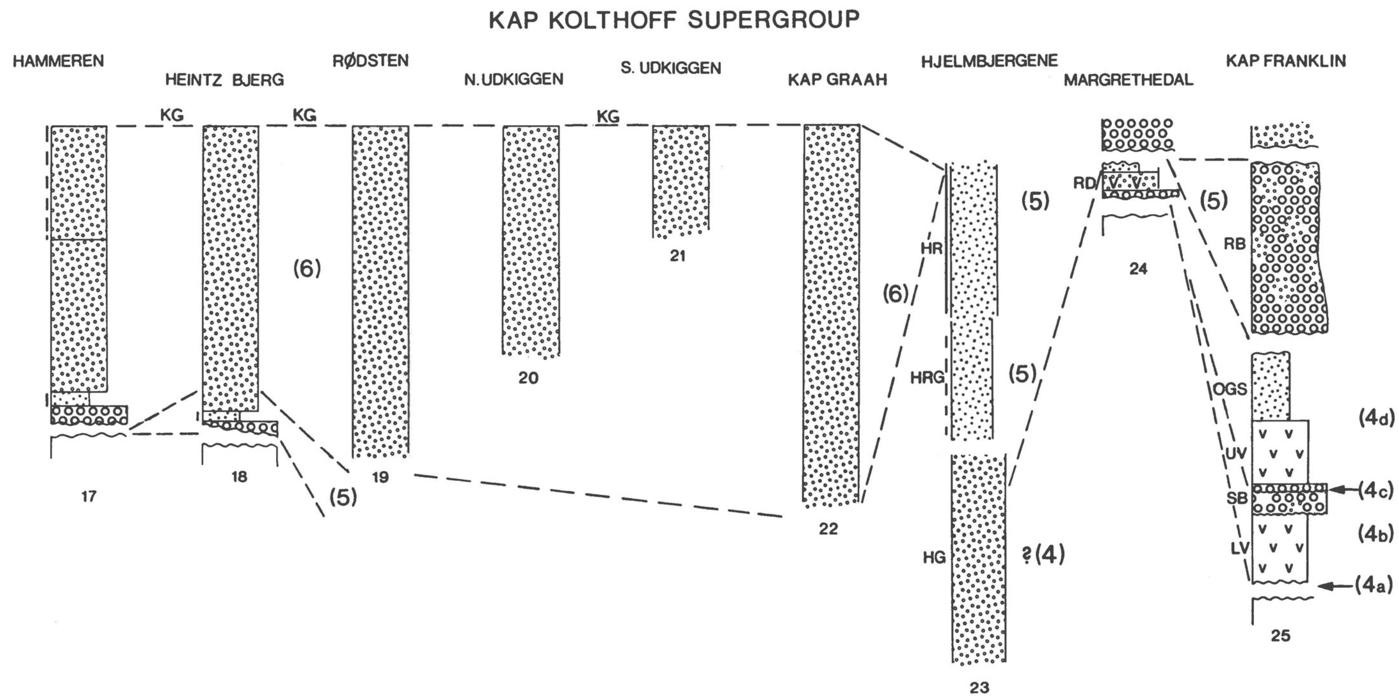

Fig. 5. Summary stratigraphic columns in the Kap Kolthoff Supergroup. Numbers below each column refer to localities in Fig. 13. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

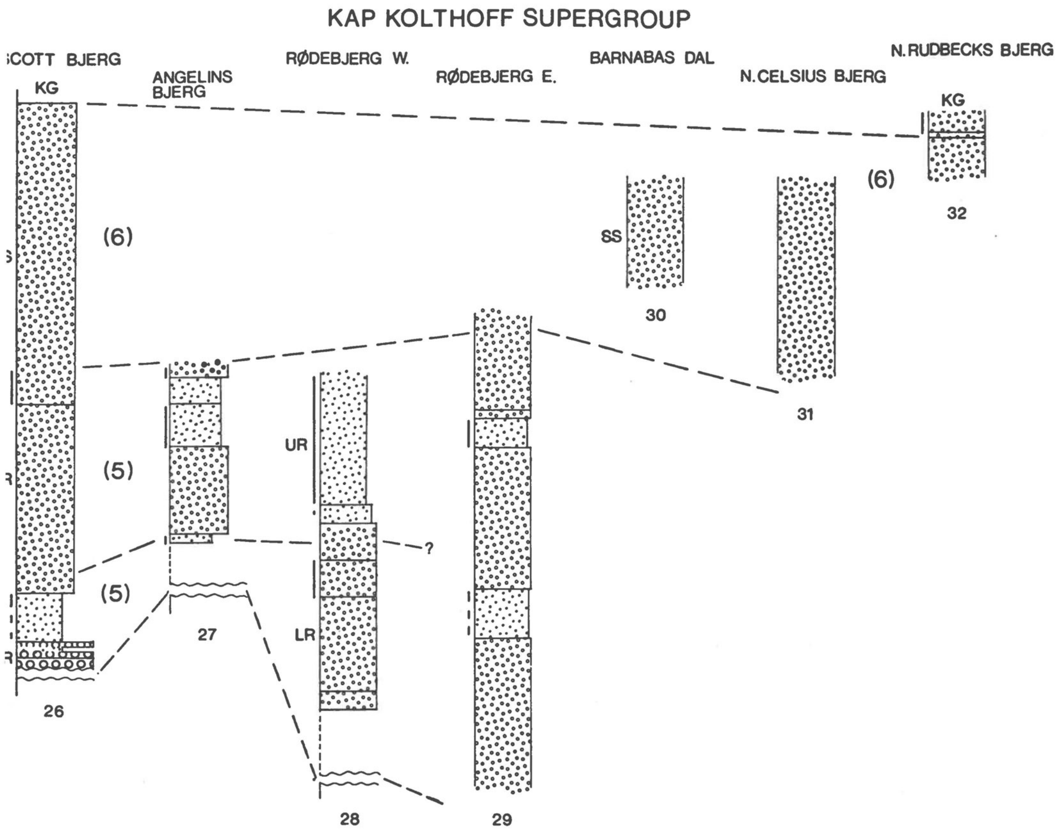

Fig. 6. Summary stratigraphic columns in the Kap Kolthoff Supergroup. Numbers below each column refer to localities in Fig. 13. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

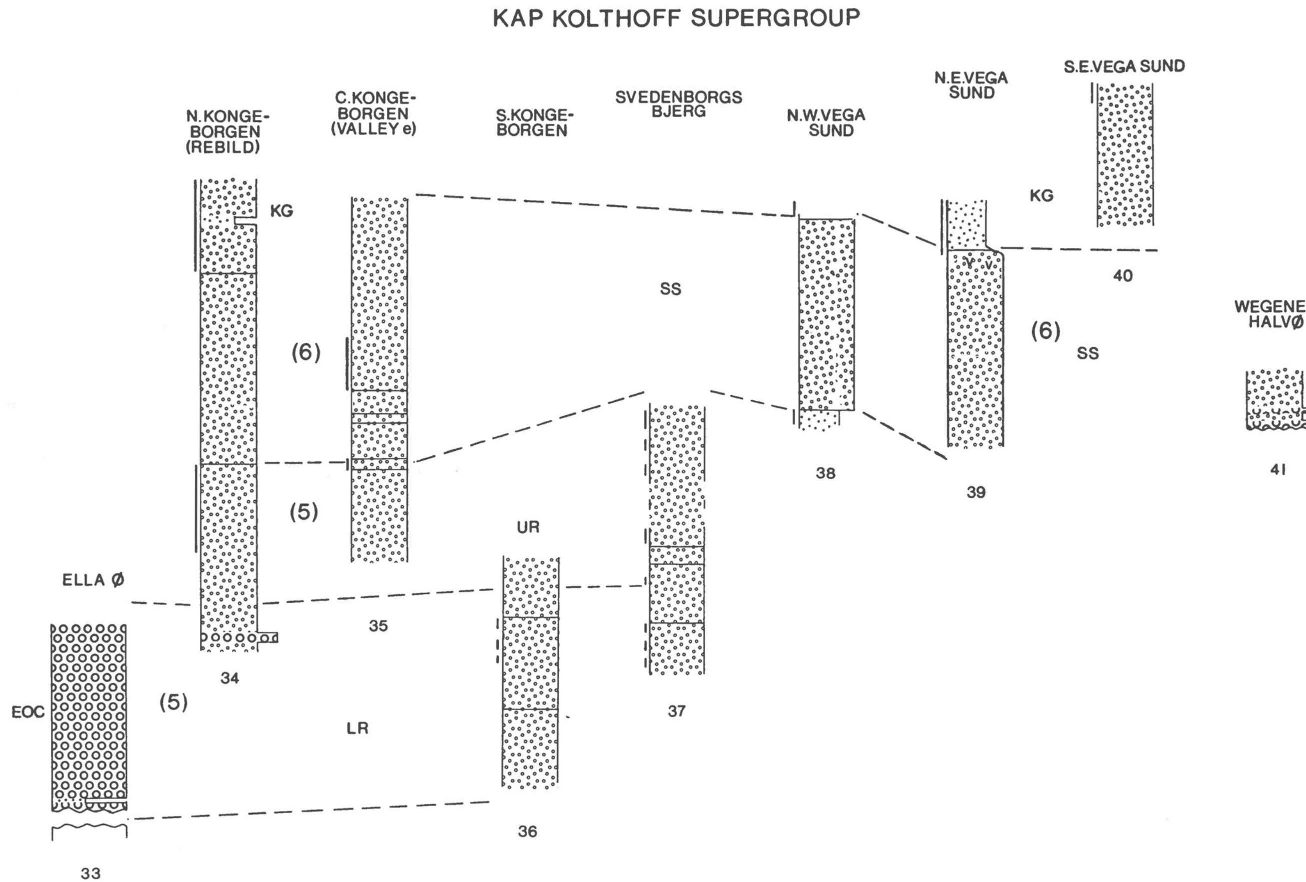

Fig. 7. Summary stratigraphic columns in the Kap Kolthoff Supergroup. Numbers below each column refer to localities in Fig. 13. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

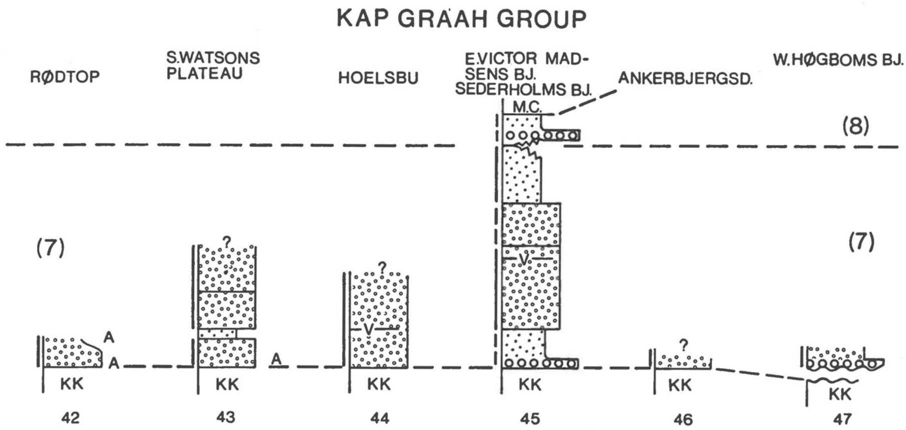

Fig. 8. Summary stratigraphic columns in the Kap Graah Group. Numbers below each column refer to localities in Fig. 14. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

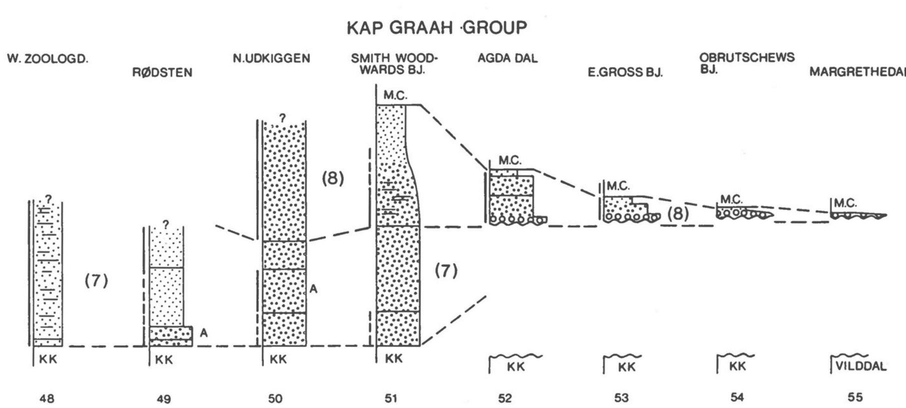

Fig. 9. Summary stratigraphic columns in the Kap Graah Group. Numbers below each column refer to localities in Fig. 14. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

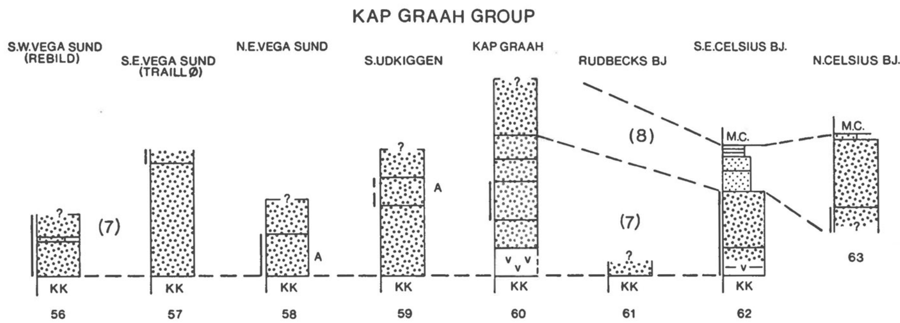

Fig. 10. Summary stratigraphic columns in the Kap Graah Group. Numbers below each column refer to localities in Fig. 14. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

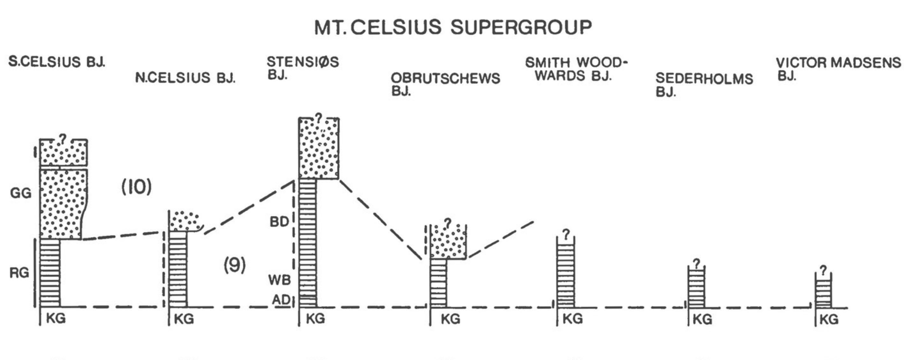

Fig. 11. Summary stratigraphic columns in the Mount Celsius Supergroup. Numbers below each column refer to localities in Fig. 12. Bracketted numbers are informal units. Stratigraphic unit terms are indicated by initial letters, as shown in alphabetical list (lexicon). See also caption to Fig. 3.

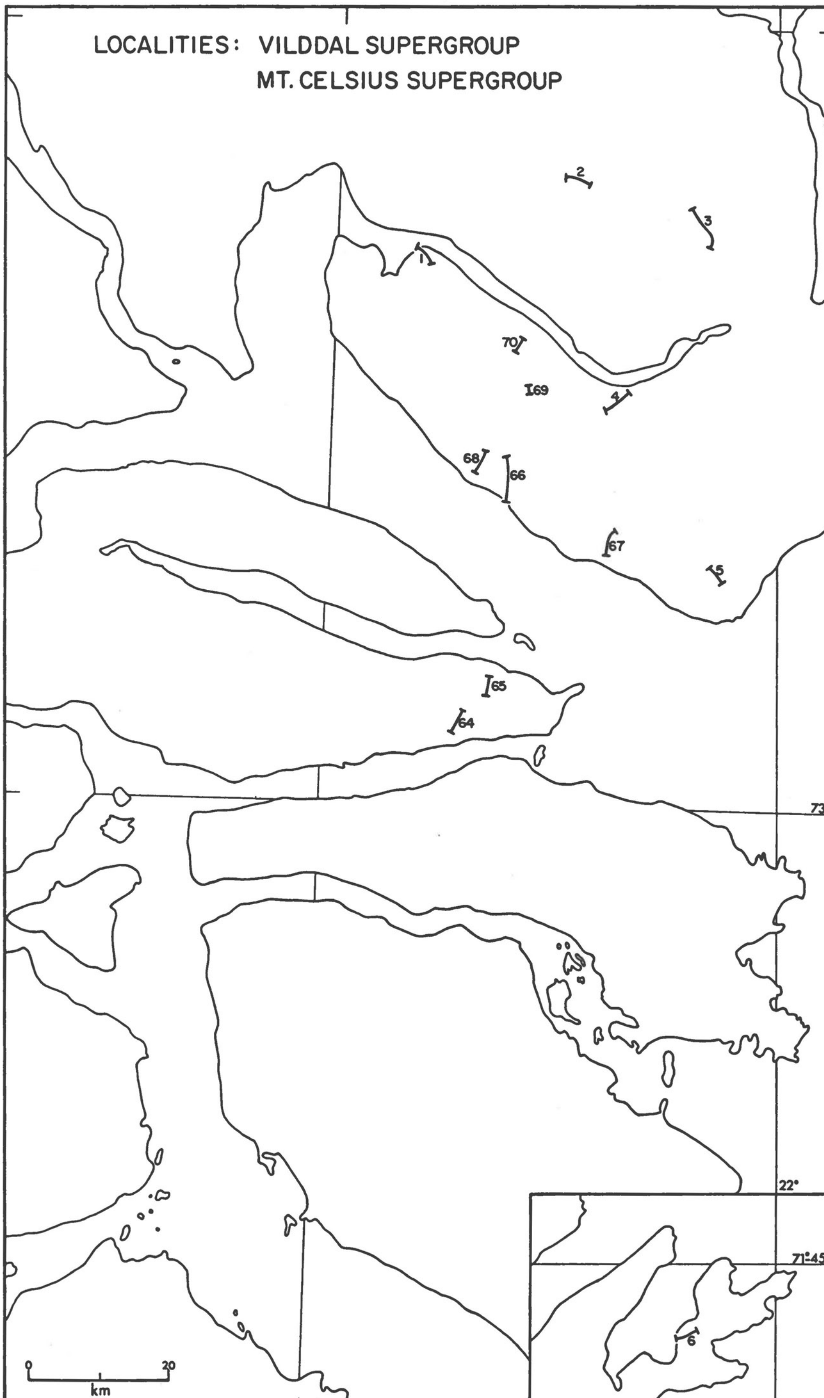

Fig. 12. Map showing localities for columns of Figs 3 and 11.

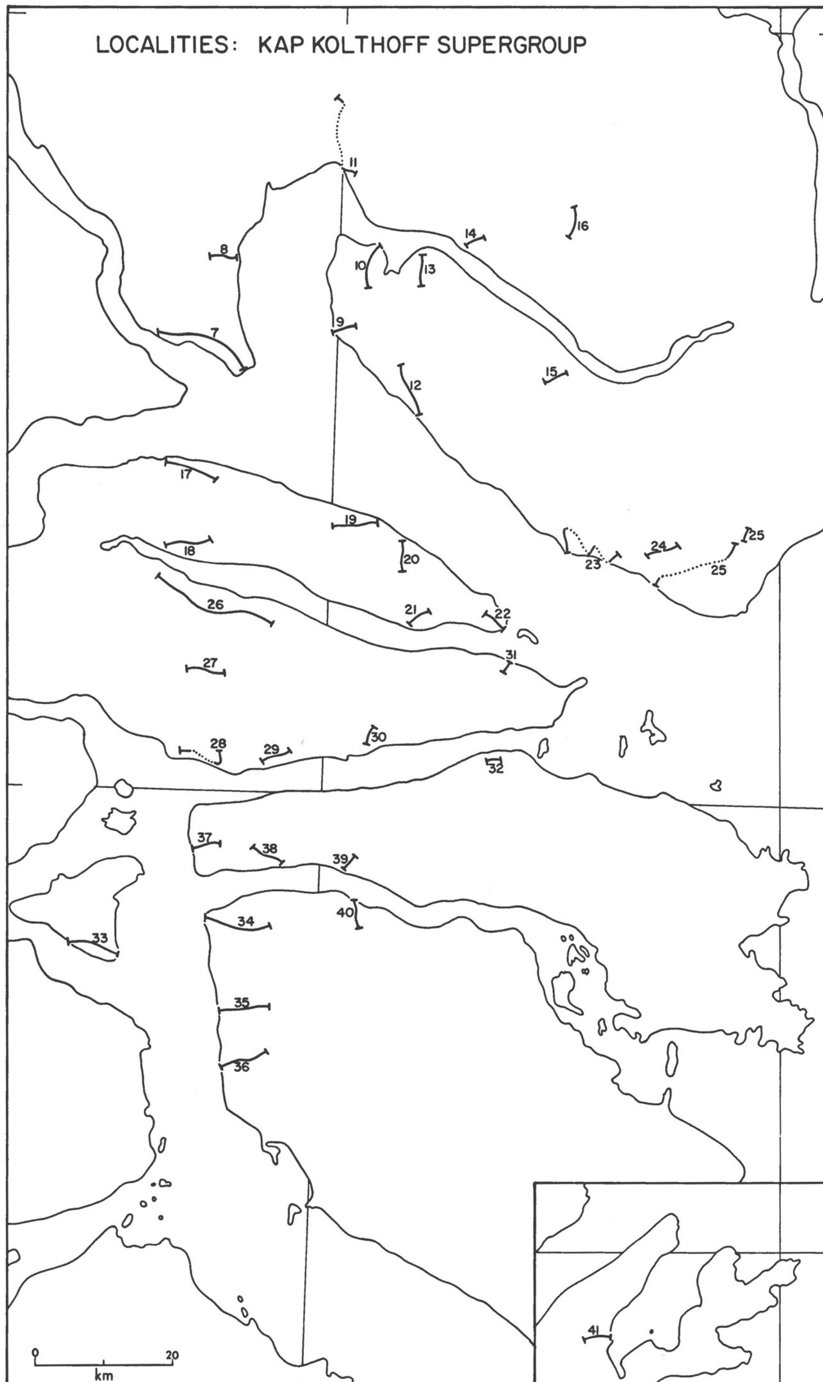

Fig. 13. Map showing localities for columns of Figs 4 to 7.

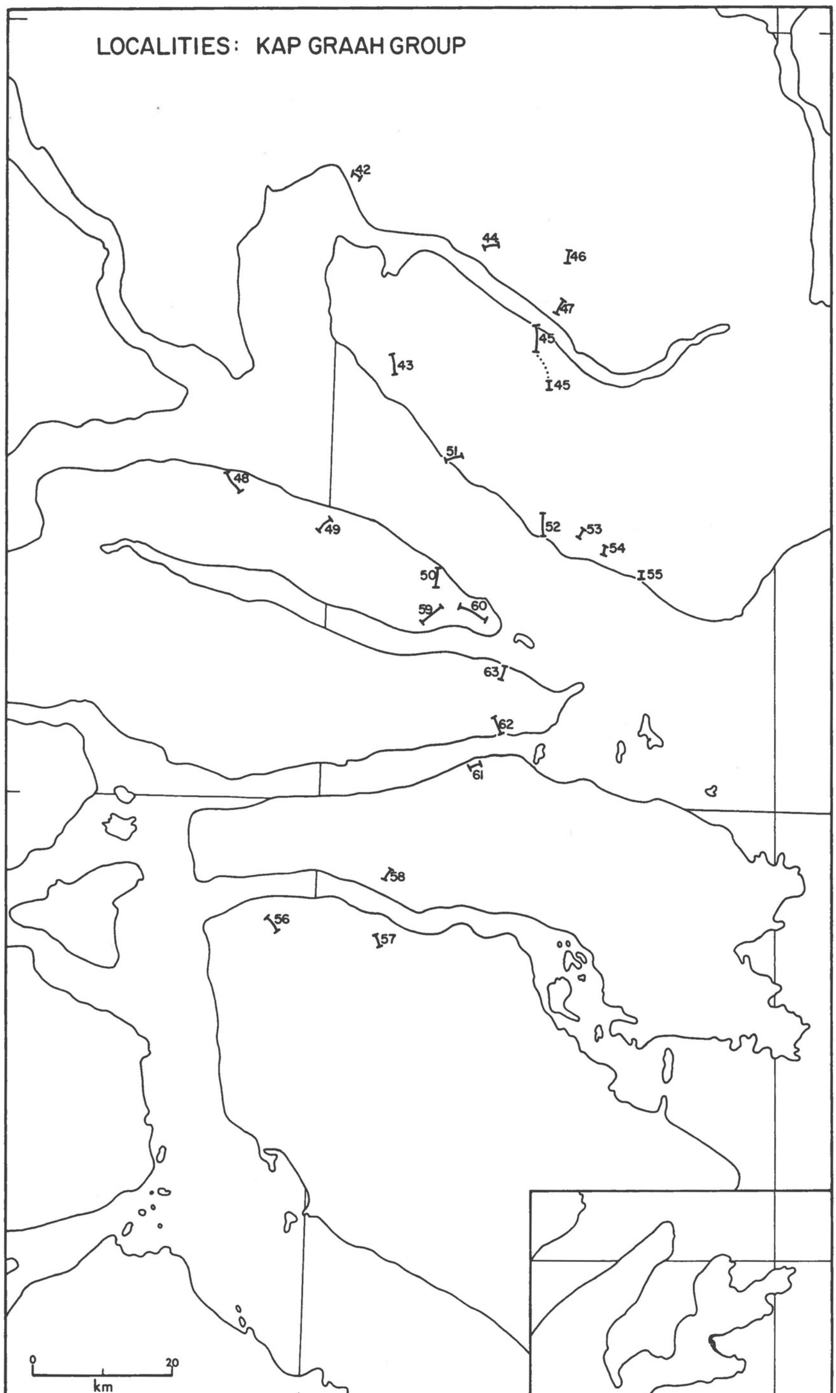

Fig. 14. Map showing localities for columns of Figs 8 to 10.

Table 1. *Hierarchy and sequence of stratigraphic units*

Note: The prefix numbers indicate hierarchy by adding extra numbers, e.g. 2.1 units are part of the 2 unit. Stratigraphic sequence *within the same level of the hierarchy* is shown by numerical sequence e.g. 2.1.2 occurs stratigraphically above the 2.1.1 immediately preceeding it in the table. There is no implication that a unit 2.1 is equivalent to other units 2.1, although it may be.

1. Pre-Vilddal Rocks
    - 1.1 Kap Fletcher Formation
    - 1.1 Inlier Konglomerat 1

2. Vilddal Supergroup
    - 2.1 Vilddal Group
        - 2.1.1 Vilddal Pebbly Sandstone-and-siltsone
        - 2.1.2 Vilddal Grey Siltstone
        - 2.1.3 Vilddal Red-and-green banded Siltstone
        - 2.1.4 Inderdalen Formation
    - 2.1 Inlier Konglomerat 2
    - 2.1 Ramsays Bjerg Group
        - 2.1.1 East Ramsays Bjerg Sandstone
        - 2.1.2 West Ramsays Bjerg Conglomerate
        - 2.1.3 Karins Dal Grey Siltstone
        - 2.1.4 Ramsays Bjerg Red-and-green banded Siltstone
    - 2.1 Nordhoeksbjerg Group
        - 2.1.1 Nordhoeksbjerg Conglomerate
        - 2.1.2 Nordhoeksbjerg Mixed Sandstone-and-siltstone
        - 2.1.3 Nordhoeksbjerg Green Sandstone
        - 2.1.4 Nordhoeksbjerg Red-and-green banded Siltstone
    - 2.1 Nathorst Fjord Group
        - 2.1.1 Basisdalen Conglomerate
        - 2.1.2 South Hesteskoen Formation
        - 2.1.3 Vimmelskaftet Formation
            - 2.1.3.1 V. Red Siltstone Member
            - 2.1.3.2 V. Grey Sandstone Member
            - 2.1.3.3 V. Red-and-green banded Siltstone Member
        - 2.1.4 West Hesteskoen Formation

3. Gauss Complex
    - 3.1 Kap Kolthoff Supergroup
        - 3.1.1 Hjelmbjergene Group
            - 3.1.1.1 Hjelmbjergene Grey Sandstone
            - 3.1.1.2 Hjelmbjergene Red-and-grey banded Sandstone
            - 3.1.1.3 Hjelmbjergene Red Sandstone
        - 3.1.1 Giesecke Bjerge Group
            - 3.1.1.1 Kap Franklin Formation
                - 3.1.1.1.1 K.F. Lower Volcanic Member
                - 3.1.1.1.2 K.F. Saxos Bjerg Member
                - 3.1.1.1.3 K.F. Upper Volcanic Member
                - 3.1.1.1.4 K.F. Østreplateau Grey Sandstone Member
            - 3.1.1.2 Randbøl Formation

3.1.1 Lower Rødebjerg Formation
3.1.1.1 Ella Ø Conglomerate Member
3.1.2 Upper Rødebjerg Formation
3.1.3 Sofia Sund Formation
3.1.1 Rødedal Formation
3.1.1 Sederholms Bjerg Grey Sandstone
3.1.2 Langbjerg Red Sandstone
3.1. Quensel Bjerg Formation
3.2 Kap Graah Group—no formal subdivisions
3.3 Mount Celsius Supergroup
3.3.1 Remigolepis Group
3.3.1.1 Aina Dal Formation
3.3.1.2 Wimans Bjerg Formation
3.3.1.3 Britta Dal Formation
3.3.2 Grønlandaspis Group

AGES OF THE INFORMAL UNITS

In this section we summarise biostratigraphic information on the ages of the succession of informal numbered units. This information is based almost entirely on the vertebrate faunas, and biostratigraphic determinations are based, unless otherwise stated, on the review by JARVIK (1961). Apart from the palaeobotanical information published in the next section, we are not aware of more recent biostratigraphic work.

Unit 1 (pre Vilddal Rocks). No fossil evidence.

Units 2 and 3 (lower and upper Vilddal Supergroup). *Gyroptychius groenlandicus*, and other small Osteolepid and *Glyptolepis*-like fossils. These suggest an upper Middle Devonian (Givetian) age (JARVIK, 1950b).

Unit 4 (lower Kap Kolthoff Supergroup, Kap Franklin Formation). Unidentifiable plant fragments.

Unit 5 (middle Kap Kolthoff Supergroup). Ella Ø Conglomerate Member contains *Glyptolepis*, *Asterolepis* and a flora (YEATS & FRIEND, 1978). These indicate an upper Middle Devonian (Givetian) age.
Randbøl Formation contains Coccosteomorph arthrodires, *Asterolepis säve-söderberghi* STENSIO, small Osteolepids and *Glyptolepis*. These suggest an upper Middle Devonian (Givetian) age (ALEXANDER-MARRACK & FRIEND, 1976).

Unit 6 (upper Kap Kolthoff Supergroup). *Bothriolepis jarviki* reported from a number of localities (YEATS & FRIEND, 1978). This may indicate an early Famennian age.

Unit 7 (lower Kap Graah Group). *Bothriolepis jarviki*, *Holoptychius* sp., *Selachii*, *Gladodus* sp. This may indicate an early Famennian age.

Unit 8 (upper Kap Graah Group). *Bothriolepis groenlandica*, *Phyllolepis orvini*, *Holoptychius* sp., indet. Acanthodii, *Nielsenia nordica*, ?*Soederberghia*. This suggests a Famennian age.

Unit 9 (lower Mount Celsius Supergroup). *Remigolepis* sp., *Oervigia nordica*, *Jarvikia arctica*, *Bothriolepis nielseni*, *Phyllolepis nielseni*, *Soederberghia groenlandica*, *Holoptychius* spp., *Eusthenodon wängsjöi*, *Ichthyostega* spp., *Ichthyostegopsis wimani*, *Acanthostega gunneri*. This fauna suggests a Famennian age.

Unit 10 (upper Mount Celsius Supergroup). *Grönlandaspis mirabilis*, indet. Arthrodira, indet. Palaeonisciformes, *Holoptychius* sp., plants (indet. Calamariaceae, ?*Knorria*). These fossils suggest an uppermost Famennian, lowermost Tournaisean (Carboniferous) age.

RESULTS OF PALYNOLOGICAL RECONNAISSANCE

K. C. ALLEN collected over 500 samples for palynological investigation during the 1969 field season. These samples came from sections throughout the succession and main outcrop area. Over one hundred of the samples were chosen as stratigraphically representative, and have been prepared in the laboratory for palynological study. The general results of this work are summarised in this section.

The samples from the lower Rødebjerg Formation on Ella Ø are well preserved and allow good dating, whilst those from a section within the Kap Graah Group are moderately preserved, and allow a more approximate dating. In samples from other stratigraphical units, spores were either absent, or poorly preserved, and accurate dating is not possible.

Vilddal Supergroup

Twenty-five samples from this Supergroup were prepared from localities in Hudson Land, eastern Moskusoksefjord, the Margrethedal area, Kap Franklin area and Canning Land.

Vilddal Group

Samples were prepared from Margrethedal, Kap Franklin and Vilddalen but only those from the latter contained spores. These were poorly preserved simple laevigate and apiculate forms which give no information on a possible age.

Ramsays Bjerg Group

Samples were prepared from Ramsays Bjerg and Høgbomsbjerg in eastern Moskusoksefjord. From Ramsays Bjerg, ill preserved plant hash was abundant but no spores were recorded. From Høgbomsbjerg a few simple undatable spores were obtained.

Nordhoeksbjerg Group

Samples were prepared from Selevebjerg in Hudson Land and these produced poorly preserved spores, some of which were identifiable. The microfloral assemblage includes

Apiculiretusispora sp.
Dibolisporites sp.
Hystricosporites sp.
Emphanisporites rotatus McGREGOR
Acinosporites macrospinosus RICHARDSON
Geminospora sp.

Auroraspora macromanifestus (HAQUEBARD) RICHARDSON
Rhabdosporites parvulus RICHARDSON
Ancyrospora sp.

The presence of *Auroraspora macromanifestus*, *Rhabdosporites parvulus* and *Acinosporites macrospinosus*, together with several grapnel-tipped spined spores, suggests a Middle Devonian, possibly Givetian age for this assemblage. The macroplant *Thursophyton milleri* was also present in this group, and this genus is at present confined to the Middle Devonian.

Nathorst Fjord Group

Samples were prepared for palynological study from Canning Land, but these failed to produce any spores. However, the progymnosperm *Rellimia* occurs in these beds with *Thursophyton*, and is a Middle Devonian plant.

Kap Kolthoff Supergroup

Sixty-four samples from this Supergroup were prepared for palynological study from localities on Ella Ø, south Ymer Ø (Rødebjerg), Strindbergs Land, western Gauss Halvø (western Moskusoksefjord) and eastern Gauss Halvø (Margrethedal area). Productive samples were obtained from Ella Ø, and Gauss Halvø (both from western Moskusoksefjord and Margrethedal).

Lower Rødebjerg Formation

Fifty-six samples were prepared from this Formation on Ella Ø, western Gauss Halvø, Strindbergs Land and south Ymer Ø, but productive samples were only obtained from the first two areas.

On Ella Ø, forty-eight samples were prepared from the basal Ella Ø Conglomerate Member of this Formation and all were productive, yielding a well preserved microflora. The Ella Ø Conglomerate Member is approximately 1000 metres thick, and outcrops on the south-east side of the island. The sequence is dominantly of conglomerates, but towards the base there are four fine grained "lake" deposits of siltstones, sandstones and freshwater limestones (see Yeats & Friend, 1978, p. 29). Three of these lake deposits have produced well-preserved spores.

ALLEN (1972) described some of the megaspores in the Ella Ø Conglomerate Member from the viewpoint of the development of possible evolutionary trends. On the basis of these trends, and on a comparison with other Devonian megaspores, a Givetian age was suggested for these rocks. Fragments of the fish *Asterolepis* were also found.

Microfloral Assemblage. The following species are recorded from the Ella Ø Conglomerate Member: —

Retusotriletes dubiosus	McGregor
Trileites langii	(Eisenack) Richardson
Planisporites dilucidus	McGregor
Apiculatisporis elegans	McGregor
Apiculiretusispora nitida	Owens
Biharisporites simplex	Mortimer & Chaloner
Hystricosporites corystus	Richardson
Hystricosporites porrectus	Balme & Hassell (Allen)
Hystricosporites reflexus	Owens
Hystricosporites harpagonis	Owens
Raistrickia aratra	Allen
Verrucosisporites cf. *proscurrus*	(Kedo) Richardson
Verrucosiretusispora pallida	(McGregor) Owens
Dictyotriletes sp.	
Foveolatisporites sp.	
Acinosporites acanthomammilatus	Richardson
Densosporites crassus	McGregor
Acinosporites macrospinosus	Richardson
Samarisporites triangulatus	Allen
Samarisporites inaequus	(McGregor) Owens
Samarisporites inusitatus	Allen
Archaeozonotriletes variabilis	(Naumova) Allen
Chelinospora concinna agg.	Allen
Perotrilites bifurcatus	Richardson
Perotrilites conatus	Richardson
Perotrilites ergatus	Allen
Rhabdosporites langii	(Eisenack) Richardson
Rhabdosporites parvulus	Richardson
Geminospora sp.	
Contagisporites optivus var. *vorobjevensis*	(Chib.) Owens
Auroraspora macromanifestus	(Haquebard) Richardson
Grandispora velata	(Richardson) McGregor
Ancyrospora ancyrea var. *ancyrea*	Richardson
Ancyrospora longispinosa	Richardson

Age of the Assemblage. The assemblage may be compared in part, with the Triangulatus Assemblage in Spitsbergen (Allen, 1965, 1967), with the Wetherall Formation in Canada (Owens, 1971; McGregor & Uyeno, 1972), the Williams Island Formation in Canada (McGregor & Camfield, 1976), with the Middle Old Red Sandstone of the Orcadian basin

(Richardson, 1960, 1965, 1967) and material Fletcher (1977) and Allen have studied from the Melby Fish beds in Shetland.

Though *Samarisporites triangulatus* is very rare in the Lower Rødebjerg Formation, eleven other species occur both in East Greenland and in the Triangulatus Assemblage in Spitsbergen, which is of Givetian age (possibly extending into basal Frasnian). Particularly important is the occurrence of *Contagisporites optivus* var. *vorobjevensis*, especially in its first occurrence, which in the Northern Hemisphere appears in rocks of Middle Givetian age, becoming more common towards the top of the Givetian and part of the Frasnian.

Fifteen species recorded in East Greenland have also been recorded from Givetian and Lower Frasnian rocks of Canada. Important here again is the occurrence of *Contagisporites optivus* var. *vorobjevensis*.

In terms of species present, the Lower Rødebjerg Formation shows closest comparison with the Orcadian Basin material from Scotland. However, absence or abundance of certain species shows important differences. Firstly, the absence in the Orcadian basin of *Contagisporites optivus* var. *vorobjevensis*, *Archaeozontriletes variabilis*, and *Samarisporites triangulatus*, all of which appear most commonly above the Upper Eifelian/Lower Givetian (the age suggested for the Melby and Achannaras fish beds). Also, in the Melby Fish Beds, the most abundant spores are *Ancyrospora ancyrea* var. *ancyrea*.

On the basis therefore of comparison with other assemblages, particularly those mentioned above, a Middle to Late Givetian age is suggested for the Ella Ø Conglomerate Member of the Lower Rødebjerg Formation.

Within the fine grained "lake" deposits, fragmentary macroplant remains are abundant. Amongst the specimens identifiable to generic level, are *Svalbardia* and *Pseudosporochnus*, both Middle Devonian plants.

Western Gauss Halvø

Four samples were prepared from western Moskusoksefjord, from a stratigraphic level probably equivalent to the Lower Rødebjerg Formation, and one of these samples produced a few spores. The spores cannot be identified to specific level, but the genera include *Hystricosporites*, *Geminospora* and *Ancyrospora*. No clear indication of an age can be given, but it is possibly Givetian.

Eastern Gauss Halvø, Rødedal Formation

Eight samples were prepared from the Margrethedal area but the only spores preserved were unidentifiable laevigate or simple apiculate forms, which give no indication of the age of this Formation.

Kap Graah Group

From Gauss Halvø and Ymer Ø, seventeen samples were prepared for palynological study. Those from Ainadal, Elsadal and Agdadal on the south side of Gauss Halvø were unproductive. However, from the south Central Circus Valley (see NICHOLSON & FRIEND 1976, p. 46; ALLEN 1972) on South Celsius Bjerg, Ymer Ø, moderately well preserved spores were recovered from a fine grained "lake" deposit within the dominantly drab sandstone.

The microflora includes

Punctatisporites glaber (NAUMOVA) PLAYFORD
Calamospora atava (NAUMOVA) McGREGOR
Trileites langii (EISENACK) RICHARDSON
Biharisporites sp.
Enigmophytospora sp.
Lagenicula sp. A
Lagenicula sp. B
Dibolisporites sp.
Geminospora sp.
Perotrilites conatus RICHARDSON

Age of the assemblage

The actual species list is not particularly useful in determining the age of this assemblage. Two important characters can help however: firstly the overall size of the megaspores, and secondly the development of the apical prominence (see ALLEN, 1972). The size of the megaspores show a sharp increase over the size of previously described Givetian megaspores (ALLEN 1965), and are more comparable with those recorded by CHALONER (1959) from probable late Frasnian or early Famennian rocks of Canada, and by MORTIMER & CHALONER (1967) from probable Frasnian of England. Secondly, the apical prominence height, in comparison with the equatorial diameter of the spore, also increases in megaspore species from Givetian to Upper Devonian, and again the megaspores from the Kap Graah Group show closer comparison with previously described Upper Devonian megaspores.

NICHOLSON found *Bothriolepis* plates on South Celsius Bjerg just above the spore horizon, and *Phyllolepis* 200 m below this horizon. He estimates that the dispersed spore locality is stratigraphically close to the *Phyllolepis orvini* / *Bothriolepis groenlandica* / *Holoptychius* horizon on neighbouring Kap Graah (see ORVIN, 1930; SÄVE-SÖDERBERGH, 1932; JARVIK, 1950, 1961). We assign the assemblage to the upper part of our unit 7 (lower Kap Graah Group) (Fig. 10).

A Late Frasnian or Early Famennian age is suggested for the Kap Graah Group.

Mount Celsius Group

Remigolepis Group

Samples were prepared from Ainadal and Stensiøsbjerg, from dark shales, grey argillaceous limestones and grey calcareous siltstones, but all were unproductive.

Grönlandaspis Group

Four samples were prepared from the small section at the top of Mount Celsius, south-west Ymer Ø. The spores were ill-preserved, and include only *Punctatisporites*, *Apiculatisporites* and *Convolutispora*, all too poorly preserved to allow specific identification or dating.

REVIEW OF LITHOLOGICAL ASSOCIATIONS

In this section we summarise our information on the Devonian rock types generally. For this purpose, we divide them into four main associations, and these are listed in Table 2, along with approximate estimates of their volumetric importance. This estimate has been prepared by adding up the total thicknesses of each category in each of the total stratigraphic columns (Fig 3–11). These thickness figures have then been converted into very approximate estimates of the volumes represented in the main outcrop areas, using the assumption that each column is typical of a 10 km by 10 km area (the approximate spacing of the columns, Fig 12–14).

Table 2. *Proportions of lithological associations*

Lithological associations	*Relative percentages*	*Volume estimate (km^3)*
Conglomerate	9	760
Sandstone	77	6340
Siltstone	11	900
Volcanic	3	260
		Total 8260

Conglomerate Association

During the 1970's, since our field work, much sedimentological attention has been paid to the deposits of braided rivers, particularly deposits of gravel or coarser grade. Studies of Recent and Pleistocene deposits include those of BLUCK (1974, 1976), EYNON & WALKER (1974), RUST (1972, 1975) and MIALL (1977). A very useful study of an ancient gravel deposit is by McGOWAN & GROAT (1971). Much of this work has concentrated on examining the morphology, internal structure and texture of the braided river bars. There is still much need for the difficult studies that will relate hydraulic variation, over a relatively long period, to morphology and internal features, in order to establish general genetic principles. Our reconnaissance work in Greenland was not generally detailed enough to allow us to study braid bar movement, nor was much of the material suitable. But we can pick out some general points of interest concerning textural features and overall geometrical relations.

Breccias make up only a very minor proportion of the Conglomerate Association. They usually occur in distinctive, relatively small (10–100's m across and a few m thick) bodies close to an unconformity (e.g. YEATS & FRIEND, 1978, Figs 20, 26). In some cases, in particular the basal limestone breccia of the Ella Ø Conglomerate Member, there is a complete gradation from zones of in-situ bed-rock weathering and collapse within the carbonate basement rock, through breccias of one clast type, to breccias of many clast types—representing a sequence with an increasing amount of transportation.

Most of the thick conglomerates lack internal structures except for a rather general layering, often picked out by sandstone lenses or scour surfaces. These conglomerates are usually of the framework type, and the generally fine grained sandstone matrix appears to have accumulated as a void-fill. These features are characteristic of the "massive or crudely bedded gravel" facies (Gm) of MIALL (1977), interpreted by him as the result of "longitudinal bar formation" in high gradient streams. Comparable deposits are forming today in gravel braided streams with slopes ranging from 0.5 to 7.2 m/km (MIALL, 1977, Table IV).

The massive or crudely bedded conglomerates generally have a mean clast diameter of 10 cm or less, though individual clasts reach 1 m. Cross-stratification in Greenland conglomerates (YEATS & FRIEND, 1978, Fig 40–42) is relatively rare, and seems to be characteristic of rather finer clast sizes, presumably because slipface accretion does not readily occur in coarse gravels.

Some outcrops exhibit an alternation of minor conglomeratic units with either sandstone or siltstone units. The conglomerates may be thin sheets (e.g. ALEXANDER-MARRACK & FRIEND, 1976, Fig. 37) or small, but discrete, lenticles (ALEXANDER-MARRACK & FRIEND, 1976, Fig. 24). These alternations seem to be characteristic of situations in which two sedimentation systems came together (two fluvial, or one fluvial and one lacustrine).

Pebbly sandstones are common locally, but will be discussed in the next section as part of the Sandstone Association. In no sense do the pebbles owe their matrix support to distinctive mass-flow processes in the sediment. In the entire area, only one unit, 5 m thick, has been interpreted as a mud-flow deposit (ALEXANDER-MARRACK & FRIEND, 1976, p. 76).

Many conglomerates that overlie unconformities provide evidence for the infilling of irregularities in the local bed-rock topography. Remarkable examples of this include the covering of several hundreds of metres of Devonian relief on Ella Ø, Hammeren, Munotbjerg and Syltoppene by the conglomerates of units 5 and 6 (middle and upper Kap Kolthoff Supergroup) (YEATS & FRIEND, 1978). Near Heintz Bjerg (YEATS & FRIEND, 1978, Fig. 31) a ravine or gully, 15 m deep, cuts into the underlying limestone topography and was filled by aggrading fluvial deposits; a remarkable length of 2 km of this gully is now exposed.

The size and shape of the conglomerate bodies show considerable variety. We can distinguish thick and thin conglomerate bodies, using an arbitrary distinguishing level of 100 m. Thick conglomerates are restricted to Units 1, 2 and 5. Where geometrical information is available it is possible to show that these bodies must have been wedges of quite limited extent, both downstream and laterally. The Nordhoeksbjerg Conglomerate, Randbøl Formation, Ella Ø Conglomerate Member and the conglomerate in south Strindberg Land cannot have extended more than a few km from a depocentre where they were many hundreds of metres thick.

Inlier Konglomerat 2 (unit 2) totals about 1000 m in thickness and is composed of regular cycles, averaging about 100 m thick, of conglomerates alternating with fine grained red sandstone intervals. These cycles are similar in lithology and size to the 'coarsening-upwards' cycles reported from the Western Norwegian Devonian basins by STEEL (1976), and interpreted as progradation cycles of alluvial fans in response to repeated tectonic events.

In contrast many conglomerates are much less thick. The unit 8 conglomerates extend as a sheet at least 20 km downstream, varying from a few metres of breccia proximally, to several metres of pebbly sandstone downstream (NICHOLSON & FRIEND, 1976, pp. 61–66). The unit 4 conglomerates have a more restricted extent. Studies of clast variation suggest deposition on small fans (10's to 100's m across) and up to 50 m thick, which were clearly influenced by the morphology of the underlying, locally volcanic, surface (ALEXANDER-MARRACK & FRIEND, 1976, pp. 22–28).

Sandstone Association

This is overwhelmingly the most abundant Devonian rock association exposed (77 %; Table 2).

We made a special effort to analyse variation in the sandstones using multi-variate techniques to distinguish groups of log samples (usually 10 m samples). This method was described by FRIEND et al. (1976a) and was used in the following detailed papers. Here we simplify the picture to bring out some general points.

Dominant grey sandstone group

Lithology. The most abundant group, forming long and continuous sequences in some stratigraphic units, is characterised by our sample group 3D (grey—m. sst—trough X) (Fig. 15). A typical 10 m sample in this group consists of totals of 7 m of medium grained sandstone, 2 m of coarse grained sandstone, and 1 m of fine grained sandstone. Other samples contain a few centimetres of fine or very fine grained sandstone or even siltstone. Sandstones are sometimes pebbly.

At least 8 m of a typical sample shows curved-foreset cross-stratification, usually with asymptotic bases to the foresets. Some foresets however are distinctly planar. An average thickness for more than 1200 sets measured in all group 3D samples in one area is 30 cm (western area; FRIEND et al., 1976b, p. 28). An average for the maximum cross-stratification set thickness in each 10 m log sample or 3D type in another area is 100 cm (eastern area; FRIEND et al., 1976b, p. 27). A mean coset thickness for this cross-stratification is 1.75 m in one area (eastern area; FRIEND et al., 1976, p. 78). Flat bedding is the next most abundant structure and commonly totals 1.5 m of a 10 m log, although the average set thickness is about 0.4 m in one area (eastern area; FRIEND et al., 1976b, p. 78). In some samples of group 3D, there is also small-scale cross-stratification and soft sediment folding.

Interpretation. The abundance of sets of similar cross-stratification points to long term accumulation in a fluvial environment where migration of groups of similar bedforms was the main mode of sand transport. The preserved set thickness (mean 30 cm; maximum 100 cm) suggests minimum depths at times of flood varying between about 2 m and 6 m. MIALL (1977) used the term "Platte type" to describe sandy sequences

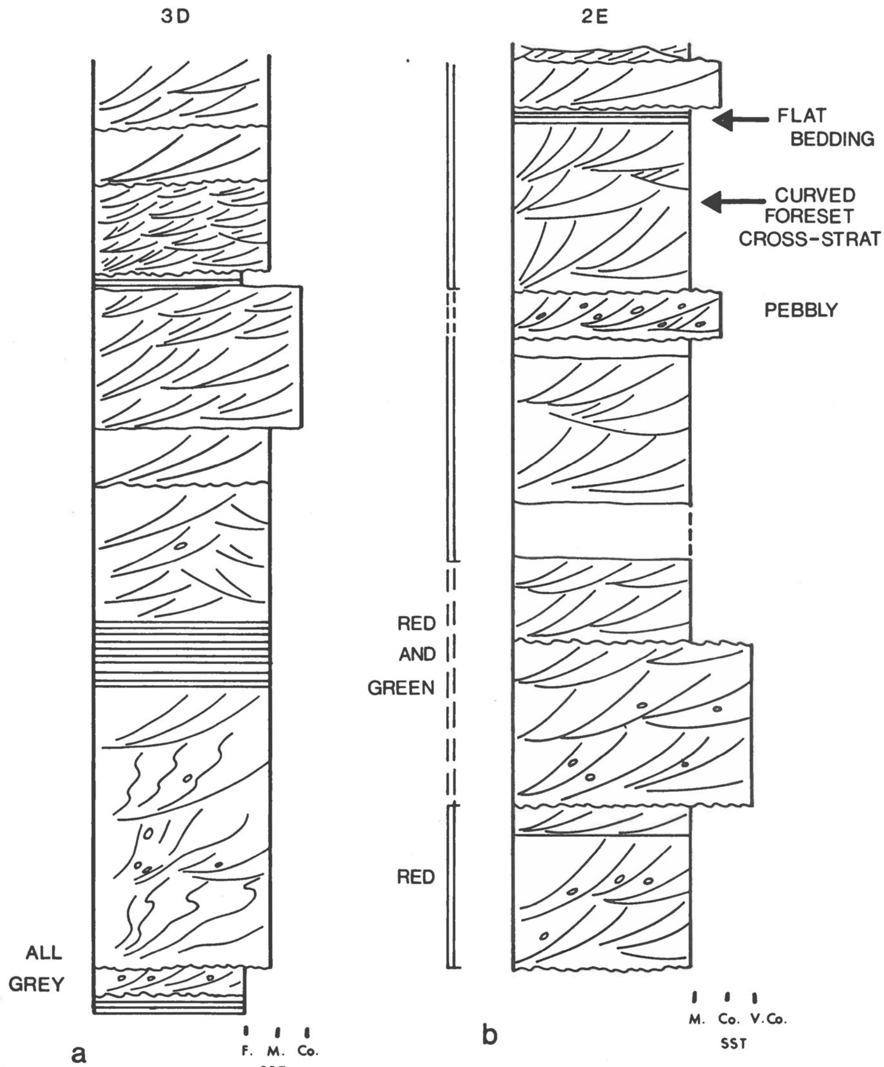

Fig. 15. Examples of 10 m logs typical of the Sandstone Association. a) The dominant sandstone group – labelled sample group 3D, b) The dominant red sandstone group – labelled sample group 2E. Sample group method is explained in our earlier papers.

dominated by cross-stratification. This "type" is based on the work of SMITH (1970, 1971) on the Platte River (Colorado and Nebraska, U.S.A.), and appears to be characteristic of "very shallow rivers, or those without marked topographic differentiation" (MIALL, 1977, p. 48). MIALL states that the dominant depositional features include his linguoid and transverse types of sand bars, expected to produce planar foreset cross-stratification. Although our Greenland rocks do provide some evidence for these bars, much of the cross-stratification seems to have been left by smaller curved lee-face dunes or megaripples.

Many of the predominantly sandy modern braided rivers described in the literature seem to be capable of depositing material like the Greenland sandstone association. However this interpretation should not be accepted without question. The virtual absence of fine grained, suspended-load beds from these sequences in Greenland shows that insignificant suspended-load materials accumulated, and this is a feature of present-day braided river deposits. But it might also imply the systematic removal by erosion of suspended load deposits by rivers that differed in their rates of migration and vertical erosion from those studied today.

Dominant red sandstone group

Although the dominant sandstone group just described is grey or grey-green, about 20 % of the sandstone outcrops are red. The most abundant red sandstone sample, forming long and continuous sequences, is classified as sample group 2E (red-m.sst—trough X) (Fig. 15). Apart from the colour, these samples are very like the commonest grey sandstone samples of group 3D (grey-m.sst—trough X). We suggest that it formed in a similar environment.

Megaripple deposition in the channels of braided rivers appears to have produced most of the cross-stratification, although some of the more planar foreset types may reflect sedimentation on the lee of linguoid-transverse sand bars, as in the Platte type of braided river sedimentation (Miall, 1977). We suggest that the redness points to an early prevalence and subsequent maintenance of oxidising conditions in the pore water of the sediment (Friend, 1966), and that this may have been associated with particularly efficient pore-water movement in the alluvial systems which later became red.

Some of the red sandstones are probably of aeolian origin. In these cases, this is suggested by the absence of pebbles and of channel-scour features, the large size of cross-stratification sets (up to 3 or 4 m thick) and by distinctive cross-stratal palaeocurrent means (Yeats & Friend, 1978, Fig. 65). Some samples classified in groups 2C, 2E and 2F may be of aeolian origin.

Patterns of vertical variation

Cyclicity visible in large exposures of the sandstone association (Friend et al., 1976a, frontispiece) is not a result of grain size variation but of alternations of units with cross-strata and units of flat bedding. These alternations may be less than one metre thick, but may be up to 10 m

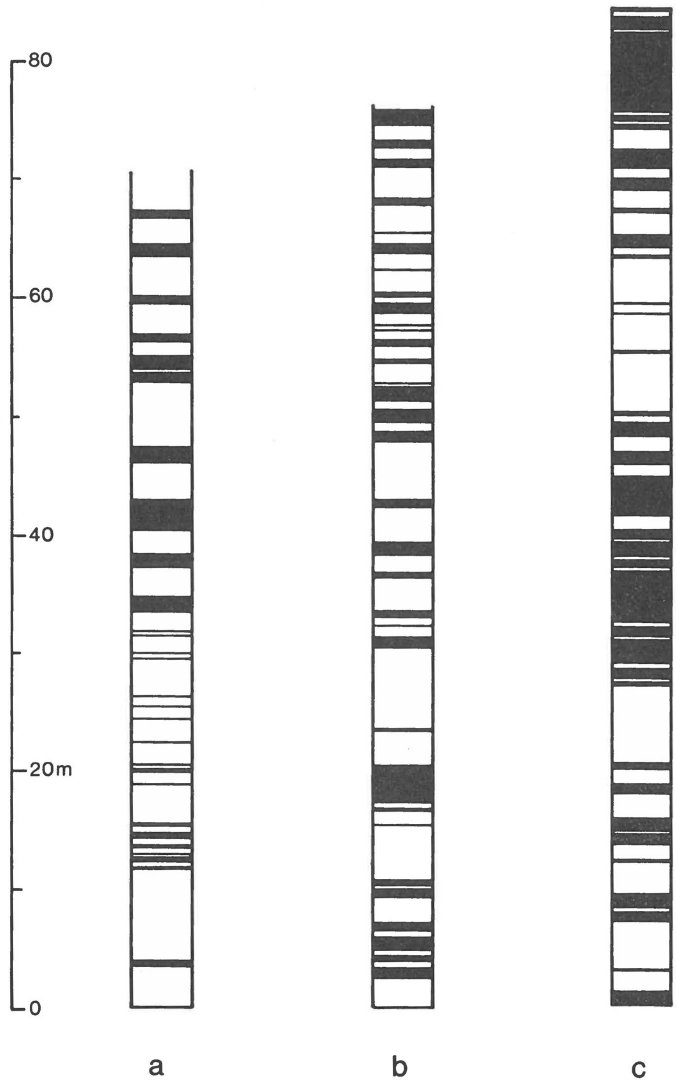

Fig. 16. Three logs from sections in the Sandstone Association showing two levels of cyclicity 1) alternations of cross- and flatstratified strata, 2) major cycles of varying proportions of these types of stratification. a) K583, Hammeren, b) K501, Scott Bjerg, c) K180, W Rødebjerg.

thick. We interpret them as the result of accumulation in deeper channel environments followed by accumulation in shallow water, bar-top (SMITH, 1971) or channel margin environments. There bar-top sediments would only be preserved by the lateral movement of the channel complex.

Major exposures of the sandstone association commonly contain a higher order cyclicity due to sequences of these alternations 20–100 m thick (Fig. 16). These 'megacycles' (YEATS & FRIEND, 1978) are more marked in some sections than in others, and seem to imply a longer term tendency for the low relief (flat-bedded) environments to regularly increase and decrease in importance. This might reflect a higher order of variation of channel position.

A 1 m alternation took 5000 years to accumulate and a 40 m megacycle took 200,000 years, assuming that they represent linear components of the accumulation of the 2 km of Kap Kolthoff Supergroup that formed over perhaps 10 m.y. of time. We have no knowledge from any present day braided river that has steadily accumulated sand over hundreds of thousands or even thousands of years and which is free from the lateral restriction of incised banks. Therefore it is not surprising that the features of these sequences can only be explained by means of rather tenuous extrapolation from rivers observed today.

Downstream and lateral variation

Grey sandstones. ALEXANDER-MARRACK & FRIEND (1976, p. 99) described examples of river systems in which downstream trends of variation in sedimentation are apparent. In their grey sandstone grouping, there was one example in which a trend of this sort could be seen (Fig. 17; ALEXANDER-MARRACK & FRIEND, 1976, Fig 66, 67, 75). Coarse and medium grained sandstones with curved foreset cross-stratification (upstream locality) passed downstream (intermediate locality) into fine and very fine grained sandstones with lesser amounts of cross-stratification (also of smaller size) and greater amounts of flatbedding and small-scale cross-stratification. Downstream from this (downstream locality), large amounts of red siltstone appear in the sequences. These siltstones alternate, on a scale of 20 m or so, with grey sandstones which are slightly coarser, on average, than those at the intermediate locality upstream.

The interpretation of this downstream pattern of variation was discussed by ALEXANDER-MARRACK & FRIEND (1976, p. 100). The upstream sandstone sequence was interpreted as the accumulation of a sandy braided river plain, with channels estimated to be of the order of 1 to 2 m deep and 15 m wide.

At the intermediate localities the large proportion of flat-bedded sandstones and the relatively thin, single-set units of low angle cross-bedding suggest that sedimentation was predominantly from flashy, fairly shallow, poorly channelised flows of the Bijou Creek type (McKEE et al., 1967; MIALL, 1977). Long-continued flows upstream seem to have been replaced by short-period flows downstream. This suggests that discharge decreased downstream because of evaporation or percolation of channel water into

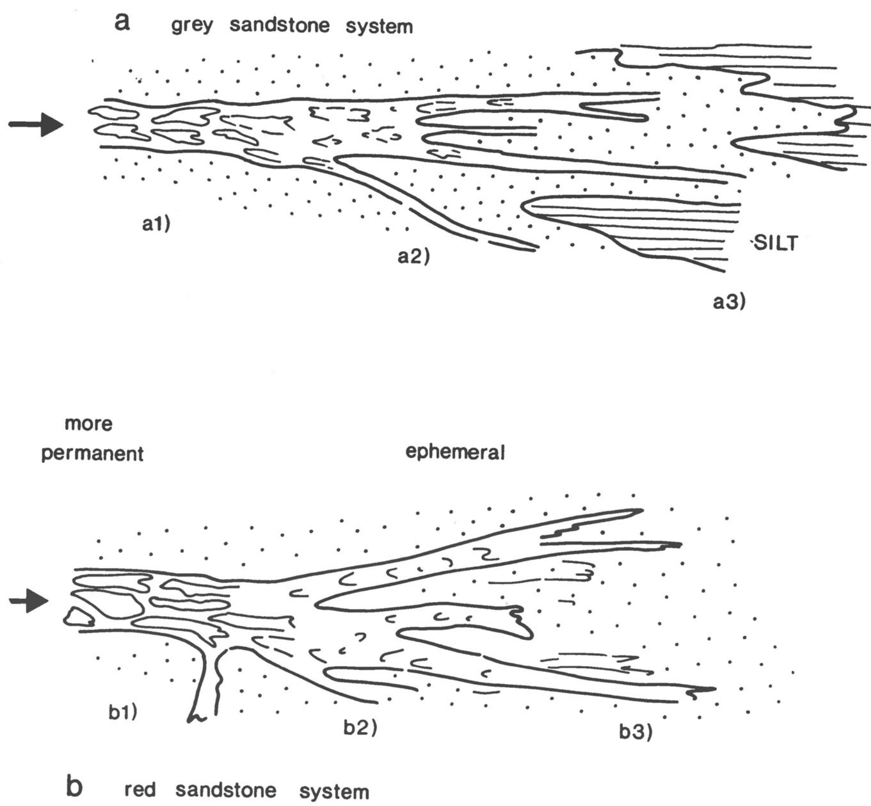

Fig. 17. Diagram illustrating downstream sedimentation changes in a) grey sandstones of the Vilddal and Kap Kolthoff Supergroup, and b) predominantly red sandstones of the Kap Kolthoff Supergroup. Proximal to distal sedimentation consists of: a1) normal dominant grey sandstone; a2) finer grey sandstones, smaller cross-strata and more flat bedding; a3) alternations of red siltstone units with fine grey sandstones. b1) grey and red medium sandstones; b2) red medium and fine sandstones; b3) red fine and very-fine sandstones.

the alluvial deposits. The abrupt interfingering of this ephemeral river system downstream with areas in which thick, cohesive silts accumulated, indicates a major new environmental factor. Between the channel complexes, areas appeared in which fine grained sediment was periodically deposited from slow-moving water, essentially ponded at times of flood. This ponding presumably extended to the centre of the basin of sedimentation. It appears that the channel complexes were being worked by the same shallow, ephemeral rivers that operated in intermediate localities upstream, rather than by rivers similar to present-day meandering types. But, the complexes were clearly separated by distinctive tongues of flood-basin sedimentation, and were abandoned periodically as the complex switched to accumulate sand in some other area.

Red sandstones. Downstream variation in a predominantly red sandstone system (middle Kap Kolthoff Supergroup) was described by ALEXANDER-MARRACK & FRIEND (1976, p. 10, Figs 35, 36, 44, 45, 55, 75) and is illustrated in Fig. 17. The proximal environment was again a braided river one, and this passed distally into an extensive area of fine grained sand with a dominance of flat-bedding. This distal region must have received sediment mainly from non-channelised, flashy sheet-floods, downstream from the main braided river complex. There is a suggestion (ALEXANDER-MARRACK & FRIEND, 1976, p. 102) that channel size increased somewhat downstream, before decreasing and vanishing.

Alluvial fans and large sediment bodies. YEATS & FRIEND (1978, p. 68, Fig 45, 46) reported on patterns of sediment variation in the western Kap Kolthoff Supergroup. They claimed that cross-stratification set thickness, coset thickness and grain-size tended to decrease downstream and/or laterally over the surfaces of the sandy fans distinguished in this area. Although their generalised diagrams do not show these trends consistently, there can be no doubt of the evidence that the trends exist at the margins of the fans, as summarised below.

The fan systems correspond to large sediment bodies, kilometres across and tens to hundreds of metres thick, distinguished by their grain size, colour and palaeocurrent directions (YEATS & FRIEND, 1978). The margins of these bodies are frequently the locations of distinctive smaller bodies of finer grained sediments. These siltstone and locally limestone bodies occur 1) where the large sediment bodies are close to the basal Devonian unconformity, and 2) where the large sediment bodies are in contact with each other (Fig. 18).

The interpretation of these local fine grained sediment bodies (YEATS & FRIEND, 1978, p. 34, 74, Fig. 54) is that they formed as the sediment fill of hollows between either the alluvial lobes of the sand and gravel fans, or between these lobes and the topography of the pre-Devonian bed-rock. A present-day analogue at the margin of an Icelandic sandur was described (YEATS & FRIEND, 1978, Fig. 28). In this case the water flow which supplies sediment to the alluvial fan (sandur) margin is partially lost by percolation into the fan. The limited flow which enters the marginal hollow transports and deposists only fine grained sediments.

A general idea of the horizontal and vertical form and size of the major sediment bodies is provided by our plots, particularly a vertical plane section through the western edge of the middle Kap Kolthoff Supergroup (Fig. 18c). A distinction can be made between the fan bodies of this marginal area, and the much larger axial-fill body that formed at the same time as the Sofia Sund system.

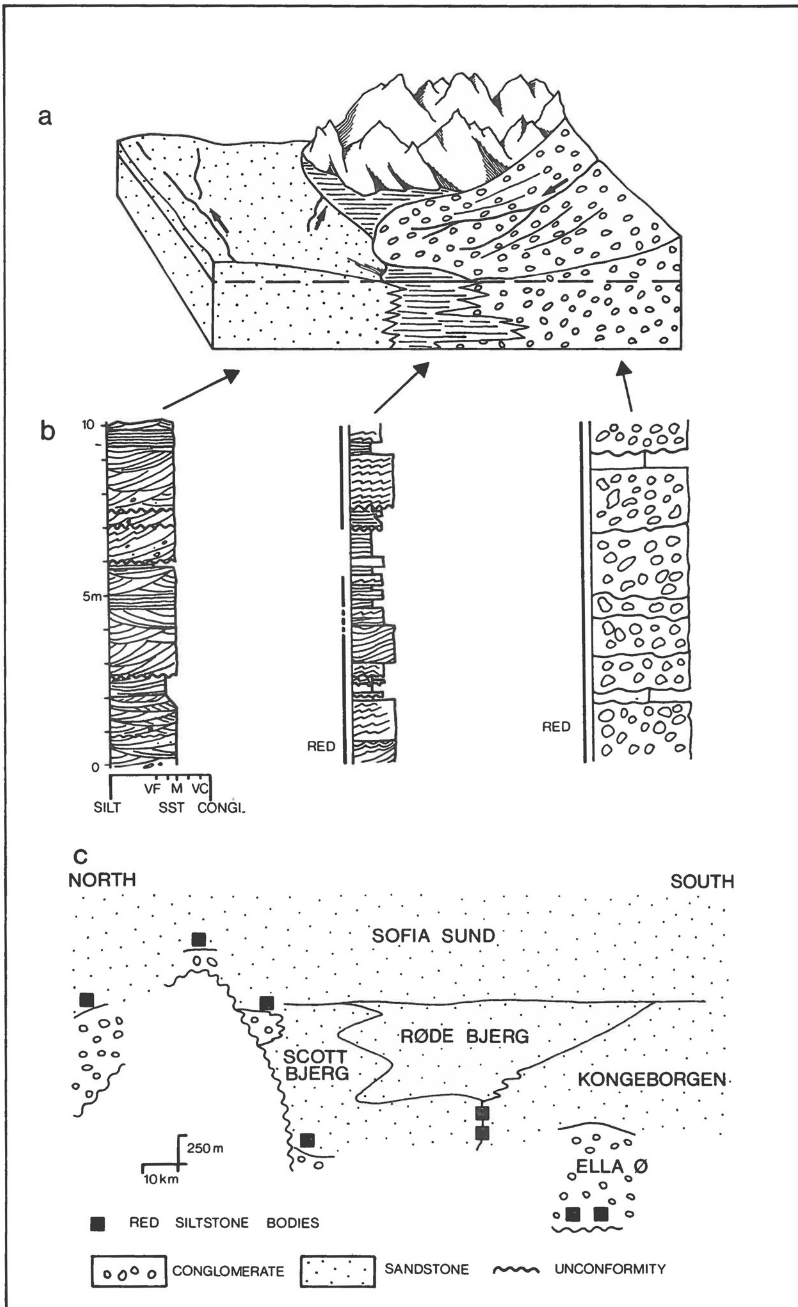

Fig. 18. Spatial relationships of major sediment bodies. a) Block diagram showing position of red siltstone bodies between marginal fans, basement terrain, and major axial sand-depositing river system. b) Typical sediment logs from the different sediment bodies, from left to right, sample group 3D, 5A, and 6. (YEATS & FRIEND, 1978). c) North-south section through marginal sediment bodies of Kap Kolthoff Supergroup.

Siltstone Association

Sequences, tens to hundreds of metres thick, composed very largely of siltstones, make up about 11 $^0/_0$ of the Devonian rocks preserved in East Greenland. They are restricted to the Vilddal Supergroup and the Mount Celsius Supergroup.

Dominant grey siltstone (4C)

Vilddal Supergroup. The Vilddal Supergroup siltstones were discussed in detail by ALEXANDER-MARRACK & FRIEND (1976, p. 107), and were interpreted as lacustrine deposits and as the fills of playas in which the fluvial input had a virtually negligible gradient.

Rather featureless grey medium and coarse grained siltstone is the background sediment type and occurs in sheets centimetres to a few metres in thickness (Fig. 19). The sheets are separated by siltsone units distinguished by the presence of internal stratification features such as cross-laminae, lenticular bedding, convolute lamination, mud-cracks and crack-fill ridges (FRIEND et al, 1976b). Most of the cross-lamination appears to have been formed by the movement of wave (oscillation) ripples, and these ripples are present on many bedding surfaces. The stratified siltstone units vary usually from a few cm up to about 30 cm in thickness.

Some further understanding of the depositional environments comes from the examination of the lateral variations of the Vilddal Supergroup grey siltstones (ALEXANDER-MARRACK & FRIEND, 1976, p. 107). Medium grained siltstones, locally with flat lamination (2 or 3 per mm), appear to have accumulated in the most offshore environment. They are the the Greenland sediment most similar to the "laminites" of the Devonian sequence of north-east Scotland (DONOVAN, 1975). In both cases the flat lamination indicates an absence (on the lake floor) of disturbance, either by organisms or currents.

From this type the lateral trend is to the appearance of some bioturbation, then lenticular bedding and finally a type with abundant symmetrical ripples and mudcracks (e.g. 4G). This trend is interpreted as extending towards more near-shore environments. It implies the existence of a lake deep and permanent enough for its offshore region to accumulate tens of metres of undisturbed and unexposed sediments, while only in the near-shore areas did wave action cause the reworking of silt sediment, and lake-level fluctuations cause periodic exposure. Occasional associated sandstones suggest the development of local beach-face surfaces or local sandbodies built by fluvial channel input. Vertebrate remains are largely unknown in these grey siltstones. This suggests that the environment was chemically unsuitable for vertebrates, although locally suitable for

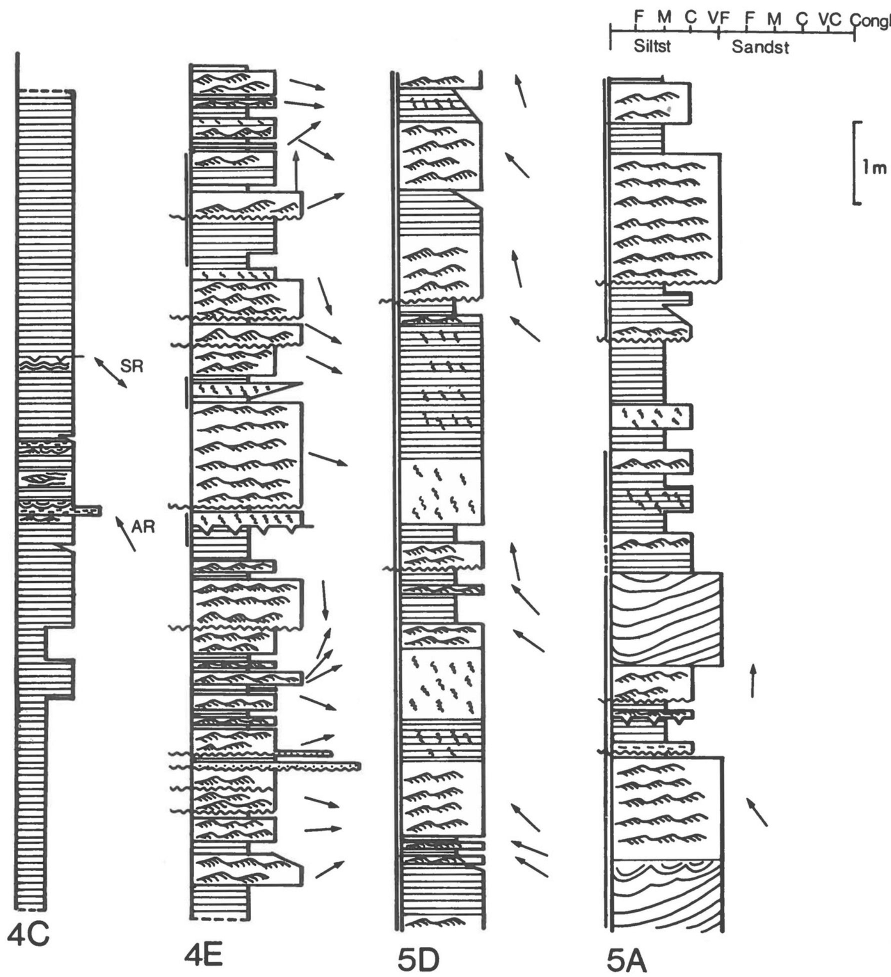

Fig. 19. Typical logs measured in different siltstone sequences. All of these are from the Vilddal Supergroup and classified according to our sample-group method (ALEXANDER-MARRACK & FRIEND, 1976). 4C (grey – m., co. siltstone – flat bedding), 4E (grey – co., m. siltstone – asymmetrical ripples – flat bedding), 5D (red – co., m. siltstone – flat bedding, asymmetrical ripples), 5A (red – co. siltstone, veryfine sandstone – asymmetrical ripples). AR (SR) indicates direction of asymmetrical (symmetrical) ripple. Symbols on logs indicate flat bedding, asymmetrical ripples, bioturbation, mud cracks and scoured surfaces.

sediment burrowing organisms. No evidence of chemical precipitation near or on the sediment surface has been found.

Mount Celsius Supergroup. The grey siltstones of the Mount Celsius Supergroup differ in certain details (NICHOLSON & FRIEND, 1976, p. 26, p. 104) from those just described. Discrete groups of thin siltstone sheets occur, varying in thickness from a few tens of centimetres to a few metres, and these groups are separated by medium grained siltstone intervals, metres thick, often red in the lower parts and with desiccation cracks. Within the groups, each thin siltstone sheet, with its underlying more featureless siltstone interval, is interpreted as being the result of 1) flooding of the playa, with sedimentation of suspended material, and 2) movement across the low parts of the playa of flood currents, carrying coarser silt and transporting it as bed-load possibly to be reworked by wave-action and convolution before the area dried out.

These groups or 'complexes' were built up in persistent hollows on the playa surface. These hollows were eventually filled with sediment, and then only received fine grained suspended load material at times of peak flood.

Vertebrate remains are absent, although, in this case, their absence may reflect lack of transporting power of the flood flows. The redness of parts of the siltstone intervals between the thin-sheet complexes probably reflects the relatively long period that these parts of the playas remained above the local water-table (FRIEND, 1966).

Comparison. Although similar in many aspects, the two major developments of grey siltstone in the Devonian succession of East Greenland differ in detail. On the one hand, the Vilddal Supergroup grey siltstones appear to have formed in a major lake which relatively continuously accumulated at least 300 m of offshore sediment, over a period presumably hundreds of thousands, or millions, of years long. On the other hand, the Mount Celsius Supergroup grey siltstones formed from sporadic flooding of a playa surface which was generally only just above or below the water table and probably did not carry lakes that existed for more than a few months at a time.

Red and green siltstones

Lithology. Alternating bands of red and green siltstones, each metres to several tens of metres thick, are characteristic of the upper part of the Vilddal Supergroup. The green siltstones are similar to those described in the previous section for the same Supergroup, although they contain more current-ripple cross-stratification and more vertebrate remains. These sediments are interpreted as lacustrine, but the influence of fluvial water input on the movement and salinity of the lake water seems to have been greater.

Between these bands of green siltstone, the bands of red siltstone contain higher proportions of current produced structures, particularly asymmetrical ripples. A downstream trend of variation within the red siltstones has been reported from more than one stratigraphic unit (ALEXANDER-MARRACK & FRIEND, 1976, p. 106). This involves a downstream decrease in the proportion of small-scale cross-stratification produced by current-ripple movement, and a downstream decrease in general grain size. At the upstream end of this trend, low-angle larger cross-strata are locally present, and upstream transitions into grey sandstone are also found in a number of localities.

Interpretation. The depositional environment appears to have been broadly fluvial, with downstream flow transporting bed-load silt as current-ripples. The rivers appear to have deposited extensive sheets of silt and to have been largely unchannelised. Sheets of featureless siltstone represent sedimentation from suspension in largely stationary flood waters. The red colours shows that it was better drained (i.e. under flood-water for less time) than the featureless and laminated grey siltstone of the lake.

The scale of the banding of red and green rocks, commonly 10 to 60 m in thickness, shows that the alternations represent fairly long-period changes of local environment (the order of 50000 years). They may either reflect major movement of the alluvial lobes (or deltas) that built out into the lake, or they may reflect repeated crustal warping.

Although thin red intervals abound in the grey siltstone sequences of the Mount Celsius Supergroup, large-scale alternations of red and green siltstones are not clearly developed.

Red siltstones

Sequences of red siltstones, thicker than several tens of metres, occur in the Vilddal Supergroup (Vimmelskaftet Formation, Red Siltstone Member), the Kap Kolthoff Supergroup (Kap Franklin Formation, Saxos Bjerg Member) and the Mount Celsius Supergroup (Aina Dal Formation). Detailed information is only available for the Vilddal and Mont Celsius Supergroups.

Vimmelskaftet Formation. The Vimmelskaftet Formation Red Siltstone Member shows a general trend of sediment change downstream (Alexander-Marrack & Friend, 1976, p. 85, 103). This involves a decrease in grain size, with the disappearance of very fine sandstone beds and the dominance of coarse and medium grained siltstone. There is a corresponding disappearance of large-scale cross-stratification which is normally either of the low-angle sandstone type, or of the siltstone category (Friend et al., 1976, p. 21). Small-scale cross-stratification, due to current-ripple movements and flat-bedding become the dominant structures. Bioturbation and vertebrate remains are quite common.

This material was generally deposited from non-channelised flood flow which was often fast enough to cause movement of very fine sand

and silt in current ripples. But some local channelisation is indicated by sand-filled channel forms (ALEXANDER-MARRACK & FRIEND, 1976, Fig. 65) and siltstone-draped cross-stratification which appears to have resulted from lateral accretion on the banks of small channels (ALEXANDER-MARRACK & FRIEND, 1976, Plate 9). The decrease of grain size downstream suggests a decrease of discharge because of evaporation or water percolation.

Aina Dal Formation. A similar trend of variation was found in the Aina Dal Formation of the Mount Celsius Supergroup (NICHOLSON & FRIEND, 1976, p. 20, 98). Both upwards and towards the area of thickest sedimentation there is a transition from 5A (red—v.f.sst.—flat, asym. rip), 5C (red—co.slst., v.f.,sst.—flat asym. rip.) to 5D (red—med.slst.—flat, asym. rip.) (Fig. 19). This seems to reflect the same decrease in grain size and amount of large-scale cross-stratification.

Much of the large-scale cross-stratification again clearly results from lateral migration of one bank of small channel forms. Downstream (towards the basin centre) and later in time, the prevalence of this was replaced by a prevalence of sheet flood deposition, from either current-ripples or suspension. Burrows are quite abundant in these sediments, particularly in the proximal areas. Vertebrate fragments are relatively abundant.

Volcanic Association

Silicic volcanic rocks

There are local silicic flows and pyroclastic rocks within the Devonian sequence. Geochemically they can be characterised as alkaline or calc-alkaline (HALLER, 1971). Three periods of volcanism can be distinguished (HENRIKSEN & HIGGINS, 1976):

1) *Kap Fletcher.* Here there are about 1000 m of silicic volcanic rocks forming the base of the Devonian succession in the Canning Land-Wegener Halvø region. They belong to informal unit 1, and are probably therefore early Middle Devonian in age. Early tuffs and rhyolite are succeeded by porphyries with some rhyodacite and latite. Many generations of lamprophyre dykes cut these lavas.
2) *Kap Franklin.* The Kap Franklin Formation (unit 4), of late Middle Devonian age, contains two volcanic members which total 540 m in thickness. Flows and sills are common, and flows are frequently overlain by tuffs. They are generally alkali rhyolitic porphyries with quartz and sanidine phenocrysts (HALLER, 1971).
3) *Moskusoksefjord and Ymer Ø.* Rhyolitic flows and pyroclastic rocks, of very limited lateral extent occur within the Upper Devonian

Kap Graah Group. Occasional dykes are associated with these volcanic rocks.

Two intrusive "granitoid" bodies occur within the Devonian sedimentary sequence. The Kap Franklin stock cuts the slightly folded Vilddal Supergroup, and is overlain unconformably by the Kap Franklin Formation. Indeed, repeated uplift of the stock is reflected in the structure and stratigraphy of this overlying formation (ALEXANDER-MARRACK & FRIEND, 1976, p. 32). The Høgboms Bjerg laccolith lies within the Ramsays Bjerg Group. Its centre is of aplite granite and its margin is of alkali rhyolite porphyry. Both the Kap Franklin stock and the Høgboms Bjerg laccolith may be closely related to some of the volcanic rocks just reviewed.

Mafic volcanic rocks

Mafic extrusive rocks occur within the Kap Graah Group, the Kap Kolthoff Supergroup and in the Kap Franklin Formation Upper Volcanic Member, although they never form very large bodies. Chemically these rocks are "calc-alkaline" (HALLER, 1971). They are associated with a more extensive system of dykes and sills.

TECTONIC STRUCTURES IN THE EAST GREENLAND DEVONIAN AREA

The object of this section of the paper is to summarise our knowledge of the unconformities, folds and faults of the East Greenland Devonian outcrop area. These are the basis for analysing the style and timing of Devonian and later deformation of the local crust.

As a means of analysing the regional distribution of the structures we arbitrarily label various localities and areas, using the letters A to J. These areas are marked on the map Fig. 23. In Fig. 20, we tabulate the evidence for the age of the unconformities, using our informal numbered units, 1–10.

In the text that follows, we summarise structural information from the various areas, and then analyse BÜTLER's "orogenic phases" of earth-movement (see also Fig. 20).

We end this section with a tectonic synthesis of Devonian folding and faulting.

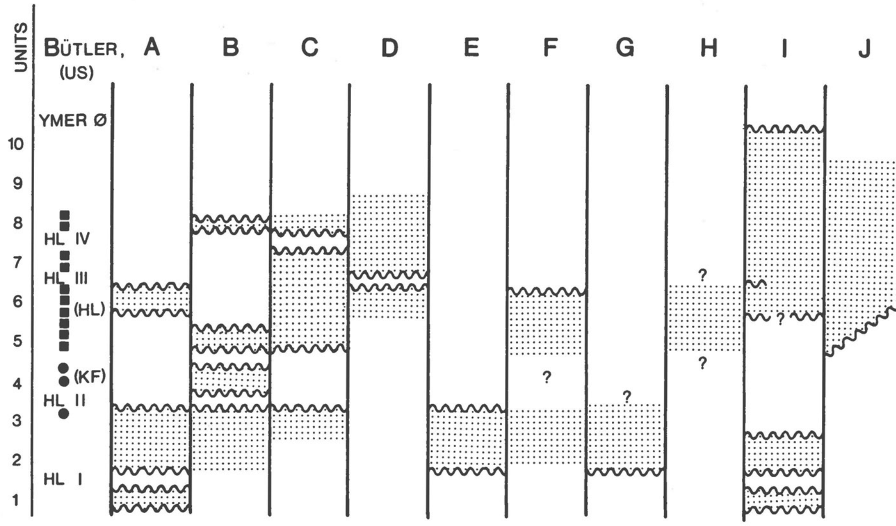

Fig. 20. Table showing evidence for age of unconformities in Devonian sequence. Units 1 to 10 are informal numbered units, outlined on p. 8. 1, pre Vilddal; 2–3 Vilddal; 4–6, Kap Kolthoff; 7–8, Kap Graah; 9–10, Mount Celsius. BÜTLER's orogenic phases are shown. Areas A–J are indicated on Fig. 21, and discussed in text.

Area A, Canning Land and Wegener Halvø (Fig. 23)

The contact between the Kap Fletcher Formation and the pre-Devonian Eleonore Bay Group is generally a fault (BÜTLER, 1948); but the presence of a conglomerate suggests an unconformity. BÜTLER's (1948, Plate 6) sections suggest only gentle folding for this pre-unit 1 earth movement.

CABY (1972, p. 27) has found evidence of "highly slumped and microfolded" dolomites in the basal Kap Fletcher sediments, and other evidence of contemporaneous mass movement within the lower volcanic parts of the Kap Fletcher Formation. He suggests that much of this syndepositional deformation may be associated with Devonian faulting (CABY, 1972, p. 34).

Below the basal conglomerate of the Nathorst Fjord Group (Units 2 and 3); there is a highly irregular unconformity surface (ALEXANDER-MARRACK & FRIEND, 1976, Plate 8). This reflects a period of uplift and gentle folding in post-Unit 1 and pre-Unit 2 and 3 times.

Sediments of Units 2 and 3 were folded, and locally overfolded, about axes trending NE–SW (ALEXANDER-MARRACK & FRIEND, 1976, Fig. 73) before the formation of the unconformity below the Quensel Bjerg Formation (Unit 6). This deformation is therefore dated as post-unit 3 and pre-unit 6.

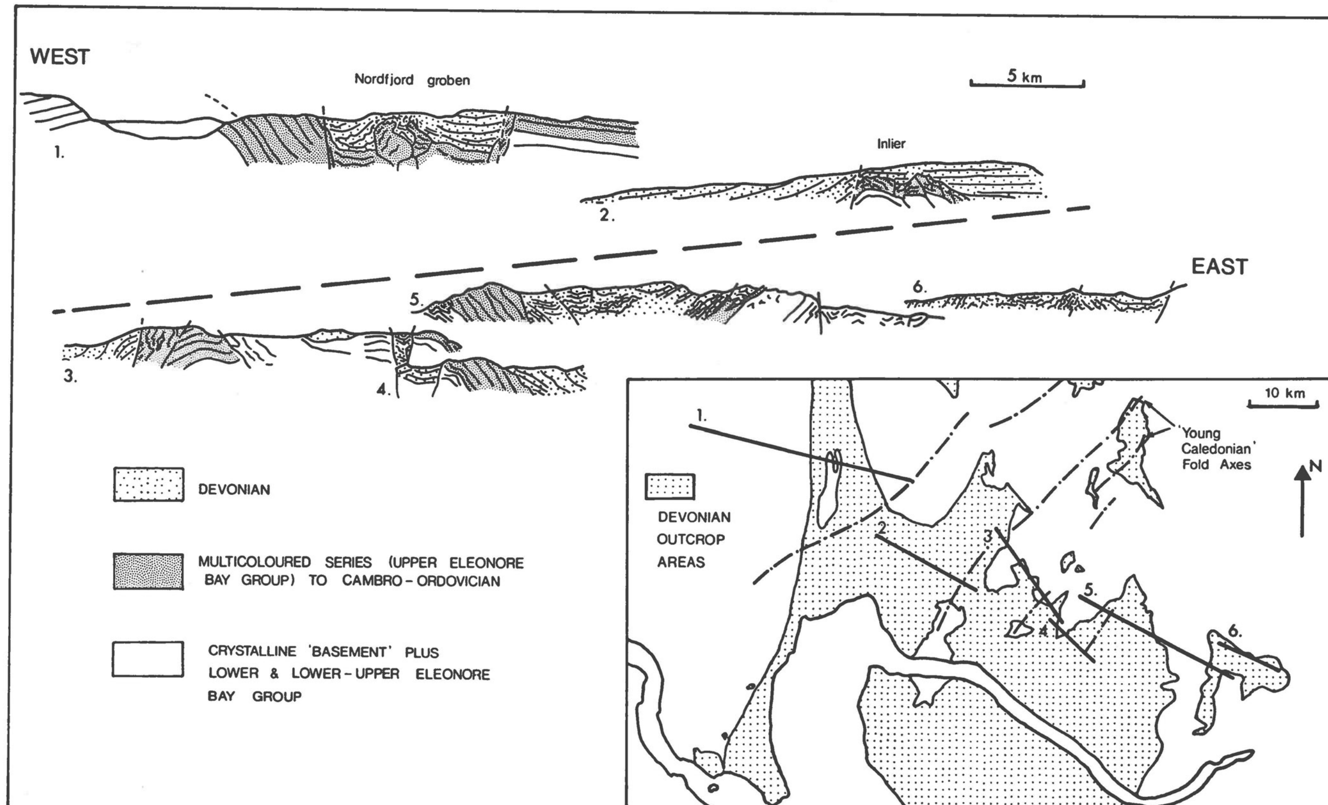

Fig. 21. Structural sections across northern area of Devonian Folding and Faulting, with location map. After BÜTLER (1975 Taf. I), and HALLER (1970). Key map shows location of Young Caledonian Folds (HALLER, 1970).

The Quensel Bjerg Formation (unit 6) exhibits broad folds, wavelength about 2 km, with axes trending NNW. These folds are overstepped by the local Permian unconformity (ALEXANDER-MARRACK & FRIEND, 1976, p. 92). This folding was post-unit 6 in age.

Area B, Kap Franklin and Giesecke Block

The continuous sequence of sediments of the Vilddal Group (units 2 and 3) was folded before the deposition of the Kap Franklin Group (unit 4). The folds constitute a relatively gentle series of large folds with axes trending E–W (ALEXANDER-MARRACK & FRIEND, 1976, Fig. 9) which determined the pattern of outcrop of the different Vilddal formations. There is also a set of folds with sharper crests, steeper limbs and smaller wavelengths, and these trend NE to NNE (ALEXANDER-MARRACK & FRIEND, 1976, Fig. 29).

During unit 4, the Kap Franklin granite was emplaced in at least two stages, generating local unconformities (ALEXANDER-MARRACK & FRIEND, 1976, p. 32) and dominating the pattern of local sedimentation and volcanism.

Unit 5 sedimentation is represented by the Randbøl Formation, highly variable and conglomeratic.

This formation is overlain with gentle discordance by Permian rocks, except where local monoclines formed and are truncated by the unconformity.

Sediments assigned by us to unit 8 occur at two localities where their relationships to older rocks can be observed (ALEXANDER-MARRACK & FRIEND, 1976, p. 44). At one of these, there is a pronounced angular unconformity, but there is no apparent discordance at the other.

A zone of intense deformation at Inderdalen shows pre-unit 8 deformation of units 2 and 3 sediments, involving faulting and disharmonic small-scale, recumbent folds (verging NW). This may have been associated with deformation along the line of the 'Main Fault' in pre-unit 8 times (ALEXANDER-MARRACK & FRIEND, 1976, p. 51).

Area C, Sederholms Bjerg (SE Moskusoksefjord) (C)

In eastern Moskusoksefjord, the Vilddal Group was block faulted (ALEXANDER-MARRACK & FRIEND, 1976, p. 62) before the deposition of the upper Kap Kolthoff Supergroup. This event was post-unit 3 and pre-unit 6.

Northeastern Sederholms Bjerg (Fig. 22b) displays a major high-angle fault separating folded Kap Kolthoff Supergroup from folded Kap Graah Group, (our unit 7) all of which are truncated and overstepped by a thin sequence of upper Kap Graah Group sediment (our unit 8)

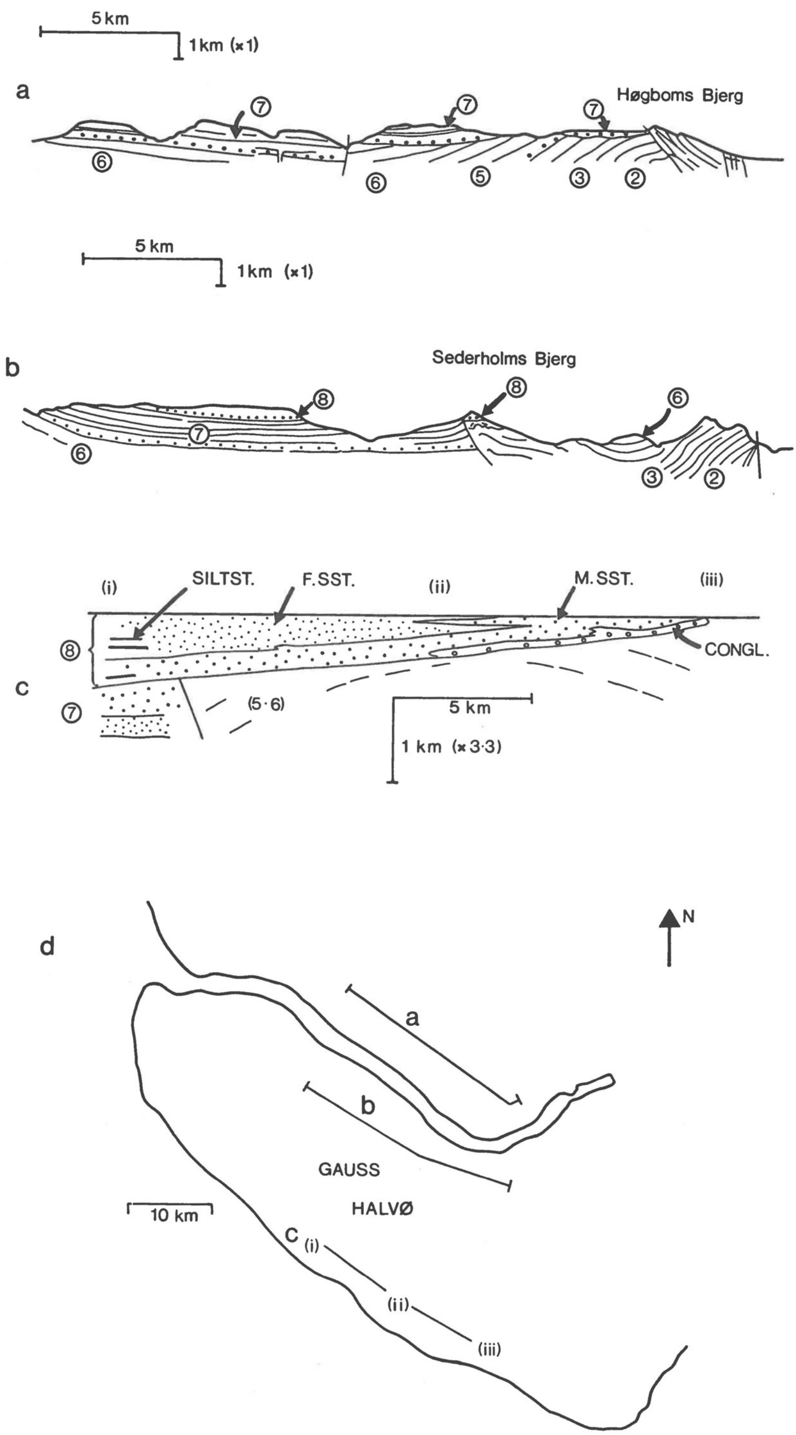

Fig. 22. Vertical sections in Hudson Land and Gauss Halvø. a) after BÜTLER (1959, Pl. 4,2), showing Høgboms Bjerg unconformity, b) after BÜTLER (1959, Pl. 4,7), showing Sederholms Bjerg unconformity, c) after NICHOLSON & FRIEND (1976, Fig 36–57) restored to uppermost Kap Graah Group geometry, showing thickness and facies variations in Kap Graah Group (7 & 8) sediments, vertical scale exaggerated, d) outline map showing line of sections a, b and c.

(Nicholson & Friend, 1976, Fig. 39). The angle of discordance decreased southwestwards and the unconformity vanishes about 1 km from the fault. Both folding and faulting occurred post-unit 7 and pre-unit 8.

An unconformity (Fig. 22c), also of pre-unit 8 age, cuts across the folded Kap Kolthoff Supergroup sediments of the Hjelmbjergene area (Alexander-Marrack & Friend, 1976). This indicates folding in post-unit 6 and pre-unit 8 times and involves the formation of major folds several km in wavelength and at least 1 km amplitude (Alexander-Marrack & Friend, 1976, Fig. 52).

Area D, Høgboms Bjerg

For a distance of about 10 km along the north-east side of Moskusoksefjord (Fig. 22a), lower Kap Graah Group sediments (Unit 7) rest on tilted Kap Kolthoff Supergroup sediments, lavas and intrusions (Nicholson & Friend, 1976, p. 77). This tilting was part of the post-unit 6 and pre-unit 7 deformation. The unconformity cannot be traced south-east of the Høgboms Bjerg–Sederholms Bjerg fault as an angular break, but a conglomerate occurs on Sederholms Bjerg which may be a continuation of the lower Kap Graah conglomerate above the unconformity (Nicholson & Friend, 1976, Fig. 39).

The major monocline below the unconformity continues NNE as the Vergys syncline which must also, therefore, be a post 6, pre 7 structure.

Area E, Nordhoeks Bjerg (E)

Our work resulted in little modification of that carried out in this area by Bütler (1957). We recognised Vilddal Supergroup sediments (units 2 and 3) resting with sharp, but essentially non-angular, unconformity on older rocks.

These unit 2 and 3 sediments were strongly deformed into open folds with wavelengths varying from hundreds to thousands of metres and often with steeply dipping limbs. These are two dominant directions of strike in the fold limbs, 350° and 50°, yielding a mean direction of NNE. High angle faults are abundant, but no single dominant direction was recognised. This folding occurred after unit 3 deposition.

Area F, Ankerbjergsdalen

Our work confirmed Bütler's recognition of units 2 and 3 in the lower part of the succession and that the coarser, sand-grade material higher in the succession should be assigned to the Kap Kolthoff Supergroup (Unit 5 ?).

The nature of the boundary between the Vilddal and Kap Kolthoff Supergroup varies from locality to locality. On Høgboms Bjerg, the boundary is a nonangular lithologic break. This break is not distinctive further north to the west of Ankerbjergselv where high-angle faults disrupt outcrop continuity. On Vergys, north-east of Ankersbjergselv, a basal conglomerate makes the Kap Kolthoff Supergroup easy to recognise (BÜTLER, 1940, Fig. 11). There is no evidence for crustal deformation, other than vertical movement, between the deposition of these two Supergroups. Indeed, the evidence for a major time gap is weak, and it may be that, in this area, deposition was more or less continuous from unit 3 to units 5 and 6.

The steep folding of the Devonian strata of this area was described by BÜTLER (1939, 1957, 1959). The particularly strong folding, overfolding and thrusting in the north are evidence of unusually strong horizontal compression in that northern area. BÜTLER considered that this deformation occurred at the same general time as the folding and unconformity on Høgboms Bjerg (area D) (i.e. post-unit 6 and pre-unit 7). We support this hypothesis and suggest that the post-unit 7, pre-unit 8 folding and thrusting on Sederholms Bjerg (area C) may be a later equivalent of the same phase of deformation.

Area G, Central and Northern Hudson Land

We did not visit this area, and the data presented here are assembled from the work of BÜTLER (1957), KOCH & HALLER (1972) and HALLER (1970).

The Devonian outliers are of two kinds. Some are erosional relics that have survived during the Cenozoic erosion of this mountainous terrain. Others have been preserved because of their structural situations, either in steep limbed synclines or in fault grabens, trending in both cases NNE or N.

In general the Devonian sediment consists of siltstone and, in this respect, is similar to the Vilddal Supergroup rather than to the Kap Kolthoff Supergroup. We have no evidence that the patterns of sedimentation were influenced by structures ancestral to the synclines or grabens. These, therefore, must have formed primarily after some unit 3 sedimentation. The Devonian sediment within these structures often contains minor structures suggesting a component of local compression. At one locality Ordovician rocks were thrust over Devonian rocks within a graben during the deformation of the older graben wall rocks (HALLER, 1970, p. 124, plate 35).

These synclines and grabens disappear to the south. The graben-boundary faults appear (HALLER, 1970) to die out in areas of Kap Kolthoff and Kap Graah outcrops suggesting that their movement may have been completed during units 4, 5, 6 or 7.

Area H, Nordfjorden, Ole Rømers Land and Stenos Land (H)

For the northern part of this region we rely again on work by BÜTLER (1957), HALLER (1970) and KOCH & HALLER (1972).

The stratigraphic position of the Strindberg Land succession is uncertain (YEATS & FRIEND, 1978). On lithologic grounds we have placed it in the Kap Kolthoff Supergroup. It is probable that the outlier sediments at the northern end of the Nordfjord graben are also part of this Supergroup.

The boundary fault and the pattern of minor structures of the Nordfjord graben has been outlined by HALLER (1970, p. 124, Fig 57–61). The boundary faults vary along their length from normal to reverse, and, in the latter case, Devonian strata have been moved over pre-Devonian rocks in some localities, and vice-versa in others. Locally folds are associated with the graben edge (HALLER, 1970, Fig. 57).

We have no sedimentary evidence to suggest that the Nordfjord graben existed during sedimentation. The boundary faults must therefore have postdated some of unit 6, and have been followed by locally variable compressional tectonics.

Area I, The 'Inlier', Western Moskusoksefjord

The numerous unconformities of the 'Inlier' have been described in detail by BÜTLER (1959, Fig 9–14).

An unconformity without major angular discordance separates the Eleonore Bay Group limestones from the sediments of Inlier Konglomerat I. This represents a pre-unit 1 episode of vertical crustal movement.

An unconformity separates folded unit 1 strata from those of Inlier Konglomerat 2 (unit 2). There is no major regional angular discordance, but the lower unit contains numerous small foids not present in the upper, and presumably reflecting post-unit 1, pre-unit 2 compression.

A further unconformity separates folded strata of Inlier Konglomerat 2 from the local basal conglomerates of the Kap Kolthoff Supergroup (probably unit 6). This unconformity demonstrates uplift of the 'Inlier' and tilting of the unit 2 strata by 20–30° before the overlying sediments were deposited. This deformation occurred in post-unit 2, pre-unit 6 times.

An unconformity appears to separate the basal conglomerates of the Kap Kolthoff Supergroup from the main body of the Supergroup (BÜTLER, 1959, Fig. 9). However, no single unconformity surface is exposed and it may be that this is a "progressive discordance" (RIBA, 1973; BRYHNI & SKJERLIE 1975) caused by syn-depositional uplift of the 'Inlier' during unit 6.

Indeed, all the unconformities of the 'Inlier', with their increasing dip with age, suggest progressive uplift of the 'Inlier'.

Areas J1–2, Ymer Ø to Traill Ø

Kap Kolthoff Supergroup sediments rest, usually with a gentle easterly dip, against a rugged topography cut into Eleonore Bay, Tillite or Cambro-Ordovician strata. These latter strata also dip eastwards, but more steeply (YEATS & FRIEND, 1978, Fig. 26). In most areas we have assigned Devonian sediments to unit 5, but on Hammeren unit 6 sediments overlap unit 5 and rest directly on basement. We have called this feature the Hammeren horst, and it appears to be bounded to the north and south by east-west trending faults which were active in late unit 5 and/or early unit 6 times. This unconformity appears to have resulted from the passive mantling of a deformed topography of Ordovician and older rocks by the onset of a new major episode of sedimentation.

A series of broad folds with relatively gently dipping limbs deforms the whole Devonian sequence, which is not broken by any unconformity from Kap Kolthoff to the Mount Celsius Supergroups (up to 10) in the central and south-eastern parts of the main outcrop area. In the south-west, along the eastern shores of Kong Oscars Fjord, a series of folds with steep, locally inverted limbs, is cut by faults. These folds and faults appear, in east-west section (BÜTLER, 1955, p. 60; HALLER, 1970, p. 134), to have resulted from a simple overthrust of Devonian sediments over and against the basement in the west. Detailed measurements (YEATS & FRIEND, 1978, Fig. 19) suggest that, in addition to this stress field, important stresses in Traill Ø were directed to the north and north-west.

All this deformation appears to have taken place before the deposition of non-marine 'lower' Carboniferous rocks (BÜTLER, 1961).

BÜTLER's phases of earth-movement

BÜTLER recognised (1959, p. 179–182) a Devonian sequence of distinct earth-mevements, and his scheme is fully quoted in recent reviews (HALLER, 1970, 1971; HENRIKSEN & HIGGINS, 1976). Below we discuss the evidence for the different "phases" that he distinguished, and have included them in our tabulation, Fig. 20.

Hudson Land phase I

This phase was defined at the Inlier (area I), at the western end of Moskusoksefjord, where Inlier Konglomerat 2 (our unit 2) rest unconformably on tilted and eroded Konglomerat 1 (our unit 1). BÜTLER (1959) also suggested that this phase resulted in unroofing of granite to produce conglomerates in the Ramsays Bjerg Group and Randbøl Formation, but our correlation excludes the Randbøl Formation from this. Nor does it allow his contention that the Vilddal Supergroup was folded at this time.

Hudson Land phase II

This phase was defined at the Inlier (area I) by the unconformity between Inlier Konglomerat 2, and the Kap Kolthoff Supergroup (our unit 6). BÜTLER (1959) correlated this folding with structures to the north, and in the Ole Rømers Land syncline to the north-west.

Hudson Land phase III

This phase was defined in north-east Hudson Land (area F), where strata said to include the Kap Kolthoff Supergroup are strongly deformed against and over crystalline basement rocks. BÜTLER's evidence for the Kap Kolthoff age of these strongly deformed strata is not known, but this deformation does seem to correlate with the folding below the Høgboms Bjerg unconformity (area D). The Nordfjorden graben was also thought to have formed at this time. We agree that some of the folding of the Kap Kolthoff Supergroup (our unit 6) near the Inlier, and in central Hudson Land (area G) is demonstrably pre Kap Graah (our unit 7) in age.

Hudson Land phase IV

This phase was defined by the deformation of the Kap Graah Group (our unit 7) on Sederholms Bjerg (area C). These folded rocks are overlain unconformably by rocks we assign to the Upper Kap Graah Group (unit 8), although BÜTLER (1959) assigned them to the Mount Celsius Supergroup. BÜTLER also attributed to this phase much of the folding of other Devonian strata in eastern Hudson Land, but this is uncertain.

Ymer Ø Phase

This phase was defined at Gauss Halvø where all the Devonian units present (up to and including unit 10) have been deformed into gentle folds. They pass southwards and westwards into stronger folds, including thrusted recumbent folds in the Kong Oscars Fjord region. We agree that this widespread phase of deformation predated the mid Carboniferous (HENRIKSEN & HIGGINS, 1976) sedimentation now preserved to the east and south.

General comments on BÜTLER's orogenic phases

It is clear from the way he discussed their correlation that BÜTLER (1959, p. 179–82) regarded his phases as somewhat distinct, and producing synchronous effects in different parts of the Devonian outcrop area. As we have pointed out above, much of the evidence for this is weak, and we prefer to adopt a broader classification of deformational events that will be outlined in the next section.

Tectonic synthesis of Devonian folding and faulting

The detailed evidence for the timing of local deformational structures has just been described for the various constituent localities. Here we shall summarise our general impressions of infra-Devonian deformation, and outline a scheme of names to label the different episodes.

i) Early movements

These are represented by the post-Kap Fletcher Formation unconformity in Canning Land (A), and the post Inlier Konglomerat 1 unconformity at the 'Inlier' (I). The latter unconformity was used to define BÜTLER's Hudson Land phase I, but there is no evidence for the synchroneity of these two unconformities.

ii) Kap Franklin Deformation

This occurred in the very widespread stratigraphic break that exists wherever rocks of the Vilddal Supergroup (units 2 and 3) are overlain by younger sediments, particularly those of the Kap Kolthoff Supergroup (units 4, 5 and 6). This close definition of the timing of the Deformation is found at area A (Canning Land), area B (Kap Franklin) and area I ('Inlier'), and the underlying Vilddal Supergroup rocks have been folded. Similar to the situation at the 'Inlier', is the structure of another horst uplift shown by BÜTLER (1957, Taf 1, D 1), about 12 km east of the 'Inlier', but there does seem to be some doubt about the field relations here (KOCH & HALLER, 1972, map 73 Ö 2). There are other localities where folding of units 2 and 3 may have occurred, but where the folding is not dated by overlying sediment (area E, Nordhoeksbjerg; area G, North and Central Hudson Land). At three north-eastern areas, a non-angular stratigraphic break implies vertical (block) movement without any local folding (area C, Sederholms Bjerg and eastern Moskusoksefjord; area D, Høgboms Bjerg; area F, Ankerbjergsdalen).

Where local folding occurred as part of the Deformation, the fold trends have an important NE or NNE axial component (area B, Kap Franklin; area A, Canning Land; possibly of this period-area E, Nordhoeksbjerg). Granite emplacement, volcanicity and the local sedimentation of unit 4, all concentrated in the Kap Franklin area (B), are events closely linked with this Deformation. Our Kap Franklin Deformation clearly includes BÜTLER's Hudson Land phase II, but we see it as a number of linked deformational events extending over a stratigraphic interval certainly equivalent to the volcanic and sedimentary events that define unit 4, and probably equivalent to some of the sedimentation placed by us in units 3 and 5.

iii) Hudson Land Deformation

We restrict our use of the term Hudson Land Deformation to structures that can be shown to have deformed sediments of units 5,6,7 or 8 (or earlier units), and appear to have been formed during this period. This Deformation includes, therefore, BÜTLER's Hudson Land phases III and IV, but excludes his phases I and II. Many of the data for this discussion come from the syntheses of BÜTLER (1957, 1959) and HALLER (HALLER, 1970; KOCH & HALLER, 1971).

The major example of a definite dated structure of this period is the Vergys syncline (Fig. 21) of area F, which is dated as post 6, pre 7 by its continuation below the Høgboms Bjerg unconformity (Fig. 22a) of area D. This unconformity disappears as an angular discordance over a distance of a few km to the west, and the underlying fold at Høgboms Bjerg is a simple monoclinal flexure, suggesting much less compression compared with the Vergys syncline further north. At Sederholms Bjerg (area C, Fig. 22c), broadly folded rocks of units 5 and 6 were faulted against rocks of unit 7 (post 7 faulting), and overlain by rocks of unit 8 (pre 8 faulting and folding). Sedimentary thicknesses and facies demonstrate the continuation of tilting movements during the accumulation of unit 8 (Fig. 22c). At the 'Inlier' (area I), local tilting and uplift occurred before and during the deposition of unit 6. In the Nordfjorden area (area H), rocks assigned to units 6 and 7 have been strongly folded and faulted.

A major problem is to decide whether the deformation of units 2 and 3 in the peripheral areas where there are no younger Devonian rocks occurred in the Kap Franklin (units 3, 4 or 5) or Hudson Land (units 5, 6, 7 or 8) Deformations. The structures in area E (Nordhoeks Bjerg) and area G (North and Central Hudson Land) may have been formed in either or both Deformations.

The major pattern of these Hudson Land structures is a series of graben and horst (Fig. 21). Sections through some of the graben provide evidence of local crustal tension (normal faulting of unfolded strata), and there is also evidence of local crustal compression (reverse faulting with stratal folding and overfolding). This local association of tensional and compressional structures is typical of a deformational pattern involving the wrench motion of fault-defined blocks with irregular, non-planar, non-parallel boundary faults.

The trends of the major graben and horst, and of the late folds (for instance as distinguished by HALLER, 1970) average north-easterly, distinctly oblique to the north-south trends of some of the local major features e.g. the main pre-Devonian folding in the Eleonore Bay Group outcrops to the west (HALLER, 1971), or the western margin of the

Devonian outcrop. This oblique trend is similar to that of some of the local folding of the Kap Franklin Deformation.

These strongly deformed Hudson Land features cannot be followed southwards across Kejser Franz Josephs Fjord, and it seems likely that they were only produced in the northern area. Support for the limited local extent of these structures comes from the undoubtedly limited extent of the Høgboms Bjerg (area D, Fig. 22a) and Sederholms Bjerg (area C, Fig. 22b) unconformities. The upper Kap Graah Group (unit 8) of south-western Gauss Halvø provides an example of the way differential sedimentation was able to compensate for, and cover up, the effects of earlier block movements. We suggest that the major deformation was centred in Hudson Land, or further north, and was contemporaneous with effectively continuous sedimentation further south. Much of the sediment was being derived from the north, apparently at least partly from the simultaneously uplifting structures of Hudson Land.

iv) Ymer Ø phase

There is no sediment preserved in East Greenland dating from the interval between the uppermost Mount Celsius Supergroup (Famennian-Tournaisean) and the lowermost part of the "Upper" Carboniferous Namurian, (Henriksen & Higgins, 1976). The fact that the two sediment units are never found in the same stratigraphic section provides evidence for the importance of the phase of deformation that intervened. A series of large and open folds, trending northerly, and rarely with dips of more than 20°, was formed in the centre of the outcrop area. In the south-west, especially along the eastern shore of Kong Oscars Fjord, complex folds, overfolds and normal faults were formed (Yeats & Friend, 1978), and give the impression of westward movement, locally with oblique components, of the Devonian basin fill over its basement.

SEQUENCE OF EVENTS IN THE EAST GREENLAND DEVONIAN

Introduction

For this discussion we have assembled our data on a series of standard maps, one for each of the ten "units" of our Devonian succession. On each map, we have summarised the following stratigraphical and sedimentary information: 1) the pattern of dominant lithological types accumulating, 2) the thickness (hundreds of m) of the stratigraphical section, and 3) the pattern of palaeocurrents—each arrow being a mean of a group of local vector means.

One object of this work is to establish relationships between these sedimentary data, and the folds and faults that may have been occurring at the same tıme. It is often very difficult to assign particular structures to a certain unit map, because of uncertainties about the timing, both of the structures, and of the units. We therefore shall record this information in a very general way, in terms of the major deformational events discussed in the previous section, and these will be marked on all the unit maps that appear to be relevant. We can usually be more precise about the timing of unconformities, summarised for the whole area in Fig. 20. On each unit map, the presence of an unconformity below rocks assigned to that particular unit is indicated by a fine-stipple shading.

Throughout this use of the unit maps, the probability of errors in detailed time correlation must be stressed.

Early events

Unit 1 (pre Vilddal rocks) and early movements

Evidence is limited to the Inlier Konglomerat I, in the north, and the Kap Fletcher Formation volcanics, in the south. Both were preceded by a long interval (the whole Silurian period, and more), represented by no preserved sedimentation, but in both cases little folding took place in this interval. These earliest relics of Devonian events are very different fragments, and may not be synchronous, so that it is not possible to construct any broader picture of unit 1 crustal processes.

Vilddal Basin development

Unit 2 (lower Vilddal Supergroup)

In contrast, a broader picture is immediately discernible for this unit, and we refer to this as the initiation of the Vilddal Basin.

In the eastern outcrops (A, E), weak folding and peneplanation of the basement (later Precambrian, Lower Palaeozoic and Kap Fletcher volcanic rocks) was followed by the accumulation of hundreds of metres of upper Middle Devonian conglomerate, sandstone and siltstone. This material was generally deposited on an easterly sloping alluvial surface. In the south, in Canning Land (A), a local source, a massif of Kap Fletcher volcanic rocks, altered this broader regional picture. Further to the west and upstream, at the 'Inlier' (I), the sediment sequence was coarser, and was preceded by rather stronger folding, perhaps indicating approach to the area of general compression and uplift from which all this sediment was being derived.

Unit 3 (upper Vilddal Supergroup)

Major thicknesses (at least 1500 m) of sediment accumulated to form this unit, with no major break, or distinct tectonic event, between it and the preceding unit.

In the north, mean palaeocurrent directions to the south-east and south show a significant change from the easterly directions of unit 2. In the south, the palaeocurrents are also different, showing a consistent flow direction to the north-northwest. This reorientation of palaeoslopes may, we suggest, provide evidence for the uplift of important new source mountains to the north-northwest and south-southeast of the basin of sediment accumulation. We suggest that this departure from the north-south/east-west pattern of unit 2, is a very significant event, heralding the Kap Franklin Deformation.

Kap Franklin Deformation

Unit 4 (lower Kolthoff Supergroup) and deformation

This is a particularly restricted unit, being confined entirely to the Kap Franklin area (B), and our inability to extend it as a unit almost certainly reflects the difficulty of correlation, rather than the lack of contemporaneous events elsewhere. Highly varied sedimentation and volcanism are closely related to local folding, forming easterly and north-north-easterly trending folds, and to doming about the still-rising Kap Franklin granite. Paleocurrents appear to reflect these local complexities.

All other areas may have been the sites or folding of block faulting at this time.

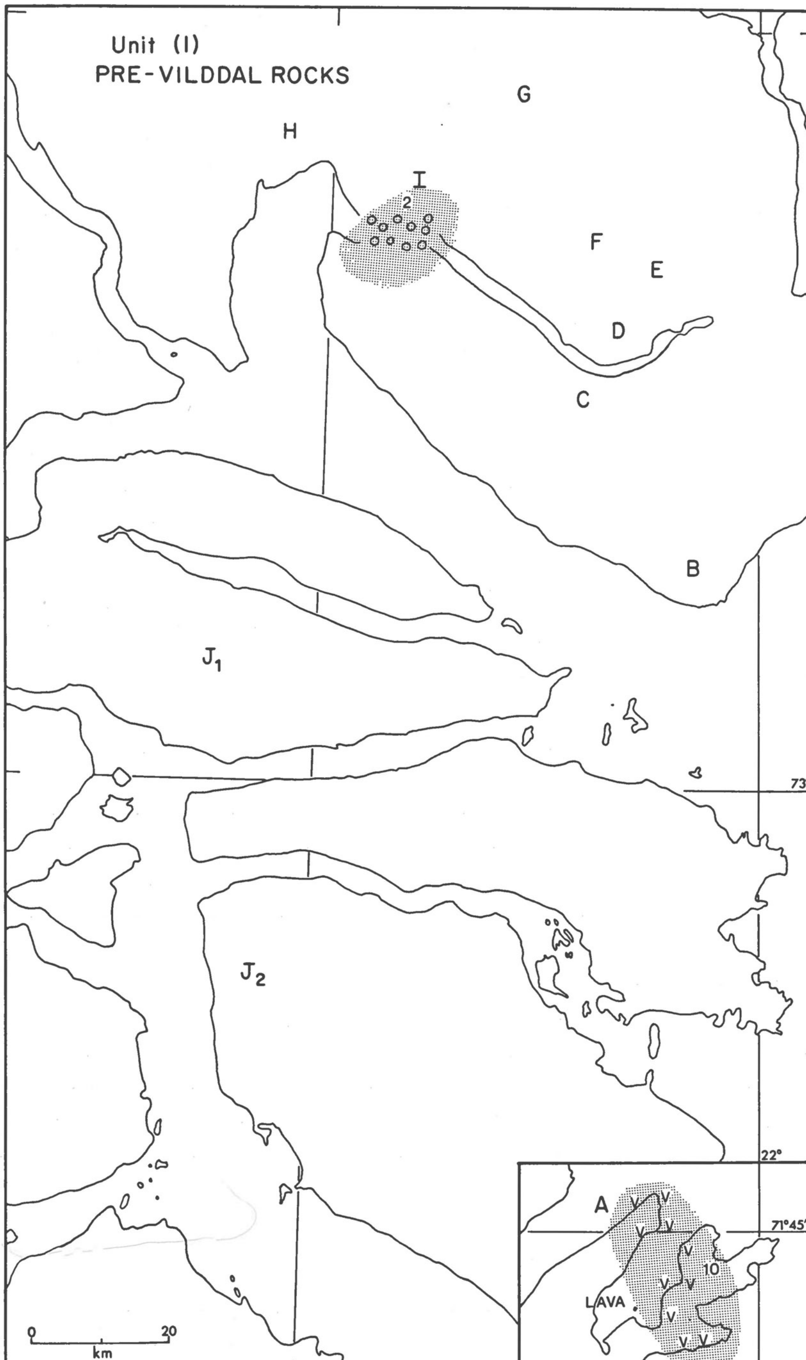

Fig. 23. Standard area map for Unit 1 (pre Vilddal Rocks). Map conventions outlined in caption of Fig. 24. Letters indicate tectonic – structural areas.

Gauss Basin development, Hudson Land Deformation

Unit 5 (middle Kap Kolthoff Supergroup)

This unit shows a dramatic change of the area of subsidence and sediment accumulation, marking the birth of the major feature that we shall call the Gauss Basin, in which the Gauss Complex accumulated.

A distinct "hinge-line" developed along the western edge of this new basin. Along it, the pre-Devonian terrain was strongly dissected by river valleys, before becoming mantled with conglomerate and sandstone, much of which accumulated in fans extending from the hinge-line. Although strong folding in the basement is often overstepped along this western unconformity, it seems likely that the folding occurred rather earlier and was not directly related to the sedimentation.

East of this marginal zone, evidence is very limited. In Hjelmbjergene and at Kap Franklin palaeocurrents suggest that fragments of the other side of the sedimentary basin are preserved, deriving sediment from the east. In view of the lack of an obvious break in the Ankerbjergselv area (F) it may be that this unit is also represented there.

It is probable that the Hudson Land Deformation was already active in the north at this time.

Unit 6 (upper Kolthoff Supergroup)

The palaeocurrents of this unit suggest the same broad pattern of subsidence that became established in the previous unit. A largely complete sedimentary basin is represented in the outcrops, with flow from the west in the west, from the east in the east, and from the north in the northern, central and southern areas. This major, axially draining basin may have been fed with water and sediment from a mountain area to the immediate north, uplifted during the Hudson Land Deformation. The "progressive discordance" on the inlier (I) and the local overlapping unconformity on northern Ymer Ø, are both evidence of localised syndepositional block movement on a similar scale. Block faulting may also have been responsible for the basal unconformity in eastern Moskusoksefjord (Sederholms Bjerg). Volcanism occurred during the accumulation of this unit in Moskusoksefjord.

Unit 7 (lower Kap Graah Group)

The pattern of palaeocurrents is similar to that for unit 6, with southerly axial drainage in central areas, and marginal drainage into this basin from both west and east sides. Volcanism was important along the eastern margin of the basin. In the Høgboms Bjerg area of north-east Moskusoksefjord (D), the sedimentation of this unit was preceded by

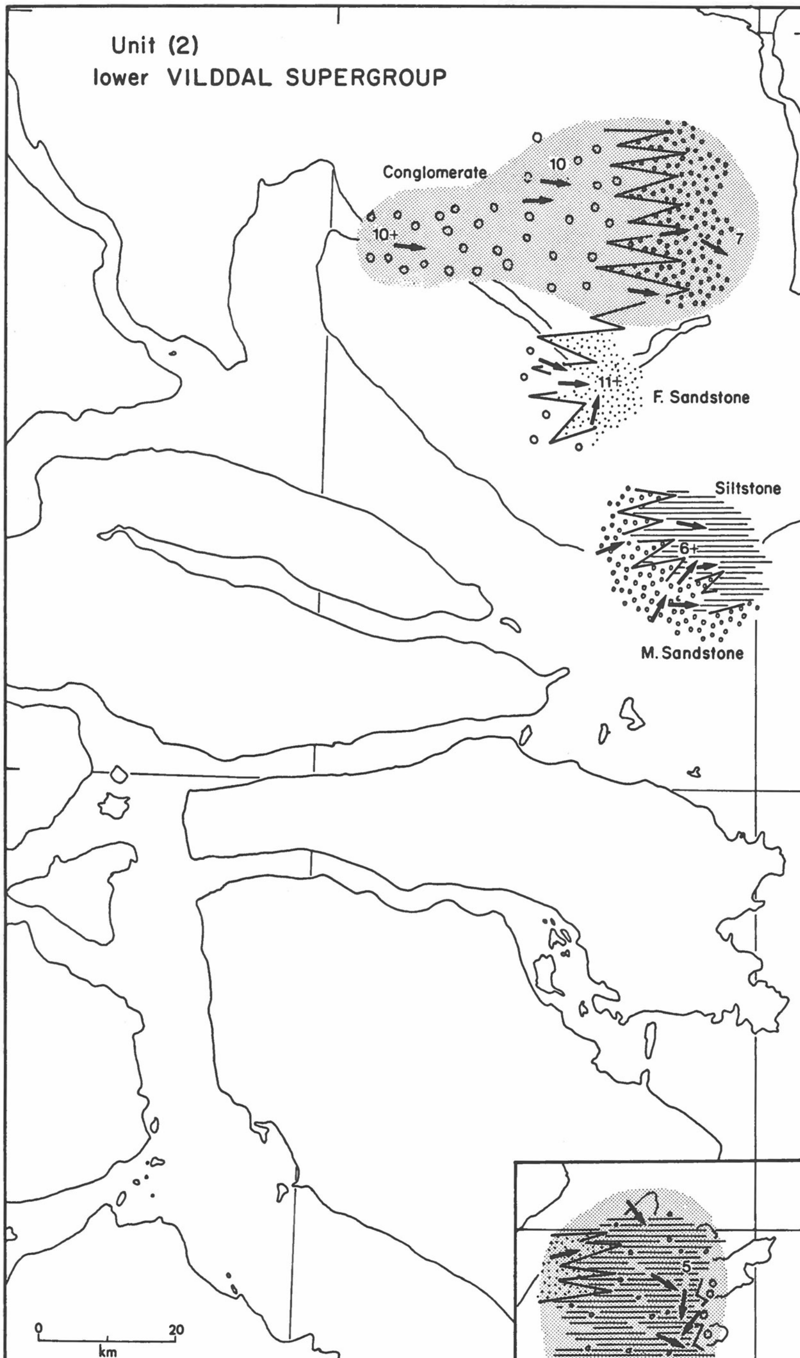

Fig. 24. Standard area map for Unit 2 (lower Vilddal Supergroup). Conventi)ns for all standard maps (Figs 23–32): Numbers are thickness in hundreds of metres. Arrows are palaeocurrent means for groups of localities. Fine stipple indicates proven underlying unconformity. Other shadings indicate respectively: conglomerate, medium sandstone, fine sandstone, siltstone. V indicates volcanics, Crosses indicate granite.

an episode in which older Devonian strata were tilted and truncated by erosion. There marginal events were typical of the block movements that formed part of the Hudson Land Deformation, although folding may have been continuing more strongly further north.

Unit 8 (upper Kap Graah Group)

The preserved records of this unit consist entirely of the eastern part of the alluvial basin, except for the material from Strindbergs Land that is only possibly assigned to this unit. Palaeocurrents are generally from the east, and the sediments show a striking change from more upstream breccias and conglomerates in the east, to sandstones in the central areas.

In these central areas sediment accumulated to a thickness of at least 900 m, and this contrasts with the thin veneer of material that accumulated further east on a folded and peneplained basement of older strata (Fig. 22c). This provides an example of the migration of the margin of a basin, by the immobilisation of the (probably faulted) margin of the unit 7 basin, and its replacement by another probably faulted, and certainly abrupt, margin a few km to the west.

The northern areas may still have been undergoing deformation and uplift at this time, and the generally sand-grade of the central deposits suggests active sediment input, but there is no more direct evidence of strong crustal mobility.

Unit 9 (lower Mount Celcius Supergroup)

The siltstone sediments of this unit suggest greater tectonic stability, because their relatively fine grade is evidence for less active sediment input. There is no other evidence for strong uplift in the source areas, although the great thickness (up to 800 m) of siltstone implies major subsidence. General palaeocurrent patterns show a new tendency towards northerly flows, and this suggests a significant change in source uplift distributions.

Disappearance of the Gauss Basin or Ymer Ø phase

Unit 10 (upper Mount Celcius Supergroup)

Only a small relic of this unit is visible. Its coarser, sand, grade suggests an increase in the activity of sediment input, and the general palaeocurrent direction is now from the west.

Both these changes may reflect a new tectonic event, the forerunner of the phase of folding, overfolding and faulting largely seen in the south-west of our area, and included, along with the general folding of the central and southern regions, in Bütler's Ymer Ø phase.

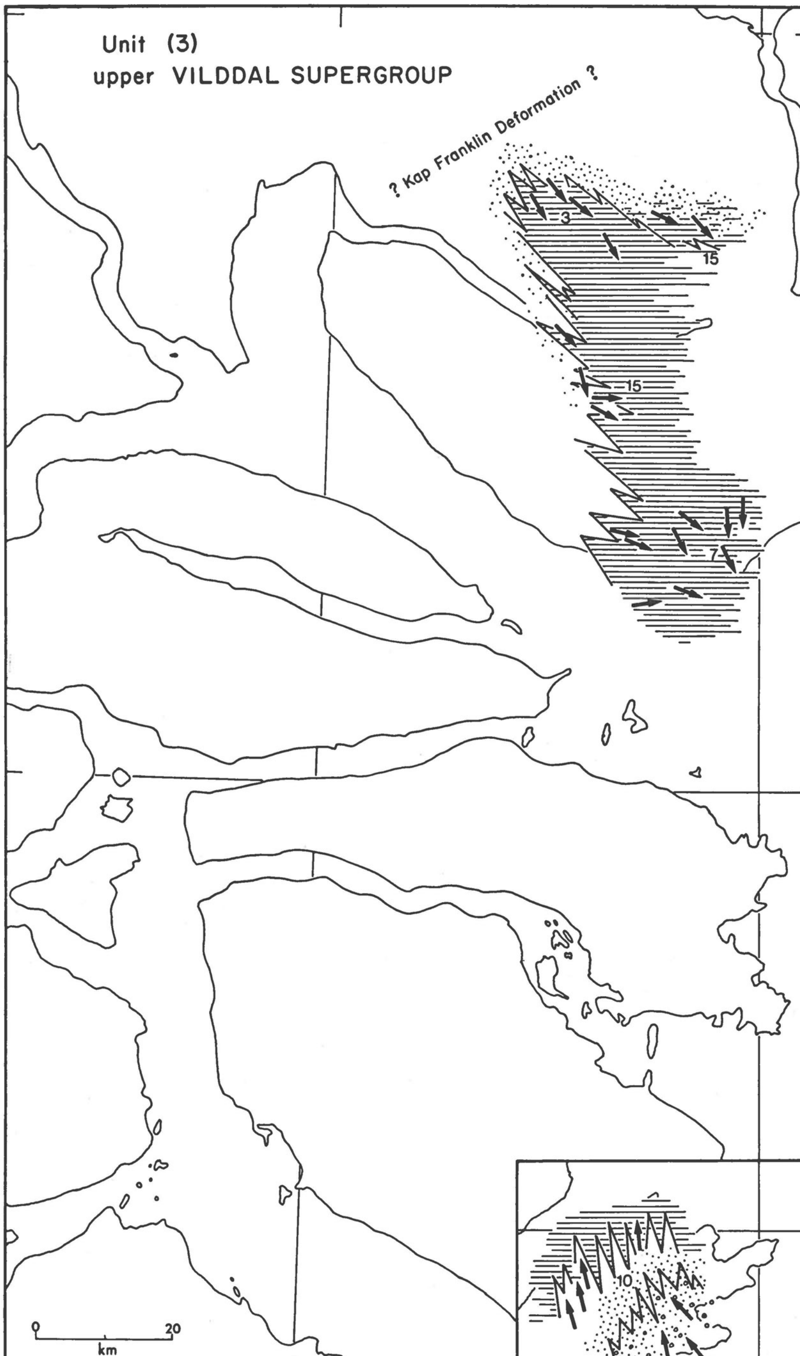

Fig. 25. Standard area map for Unit 3 (upper Vilddal Supergroup). Conventions explained in caption of Fig. 24.

DISTINGUISHING TECTONIC AND CLIMATIC CONTROL

General approach to the problem

All natural systems of sedimentation are the result of the simultaneous action, and interaction, of a very complex system of processes. Ultimately changes in the patterns of these processes, whether in space or time, must reflect changes in one or other, or both, of the two major controlling variables, tectonics and climate.

Distinguishing the effects of these two controls will, in practice, be very difficult. Tectonic controls tend to influence most strongly the size and shape of the catchments, the type of bed-rock, the amounts of topographic relief, and the gradients of the streams, although all these can also be influenced by the climate. Climatic controls most directly influence the patterns of sediment and water input.

We can make the following general points about the Greenland situation.

1) The Greenland outcrop area (maximum dimensions of 300 km by 100 km) is small compared with present-day global climatic zones. One would expect, therefore, some broad climatic uniformity, although more locally, e.g. in local source areas of different aspect, climatic factors may have differed considerably.

2) The distinctive bodies of sediment that accumulated within the Greenland outcrop area mark the existence of distinctive drainage systems. These differences may have reflected either climatic or tectonic differences, or both. Examples of differences due to contrasts of water discharge pattern have been given by ALEXANDER-MARRACK & FRIEND (1976 p. 99). Tendencies for the drainage systems to decrease in activity downstream, probably reflected decrease in rainfall inwards from the basin margin, and this idea has been reviewed earlier in this paper.

3) Changes of sedimentation affecting the whole outcrop area during a particular stratigraphical interval, may have resulted from changes of either tectonic or climatic controls.

4) Changes of palaeocurrent patterns and thicknesses affecting several drainage systems, but not affecting the whole outcrop area, seem best explained in terms of varying patterns of tectonic uplift in the surrounding areas.

Having raised these general points, we shall now discuss the roll of the two ultimate controls through the Devonian stratigraphic sequence.

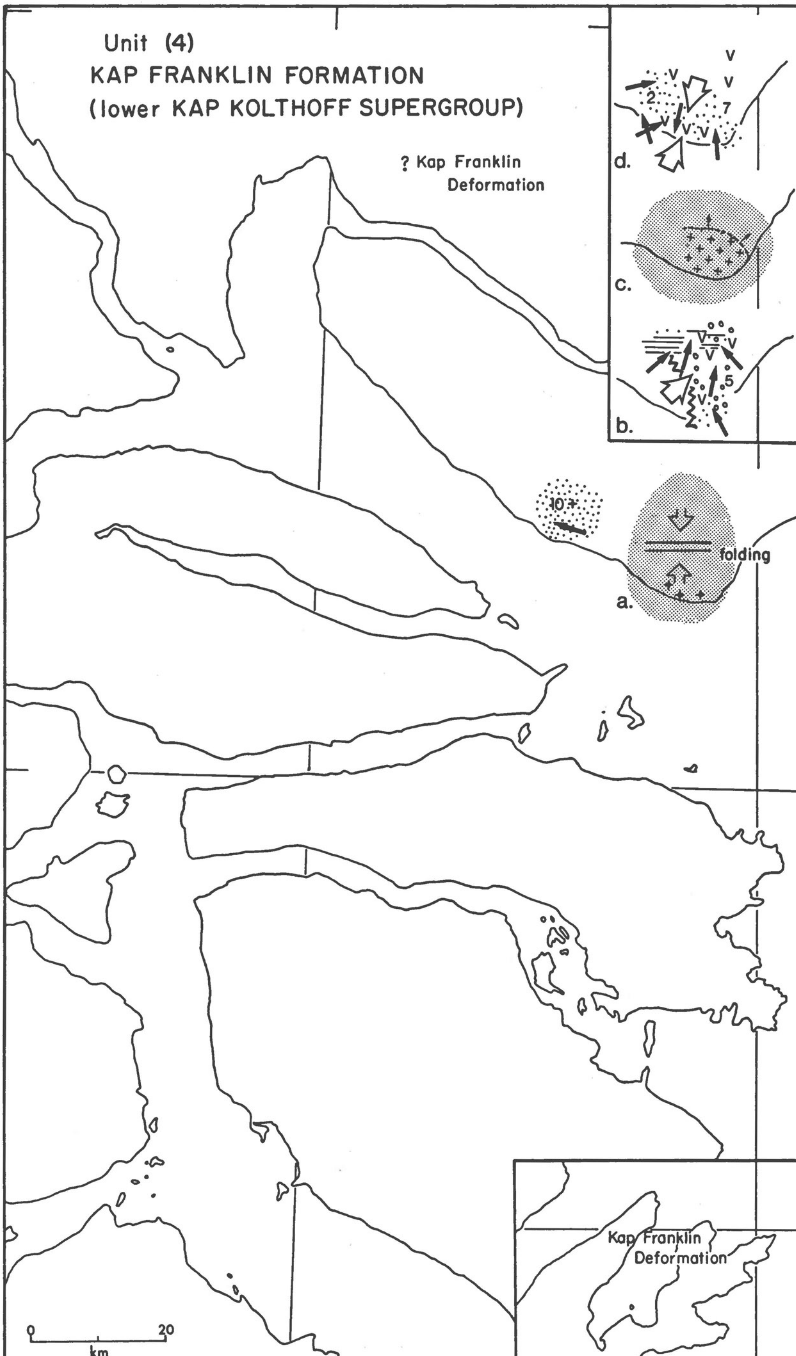

Fig. 26. Standard area map for Unit 4 (Kap Franklin Formation, lower Kap Kolthoff Supergroup). Conventions explained in caption of Fig. 24.

Discussion of sequence and type of control

In our review of the sequence of units in the East Greenland Devonian we recognised a number of important events. We shall now examine these in terms of the relative importance of tectonic or climatic control.

i) Early events

Because these events include the extrusion of the Kap Fletcher Formation volcanic rocks, they are certainly at least partly tectonic in their control.

ii) Vilddal Basin development

This major stratigraphical event seems to have been tectonically controlled, because it is recognisable as a new drainage and sedimentation pattern across the whole outcrop area. The increase through stratigraphical time in the proportion of siltstone and fine sandstone, as compared with the coarser clastic sediment, may indicate change in climate or decrease in tectonic uplift rate in the source areas.

iii) Kap Franklin Deformation

The modification of drainage pattern in unit 3, and the folding, faulting, volcanism and granite emplacement, all appear to relate to an important tectonic event.

iv) Gauss Basin development and Hudson Land Deformation

These major events must have been primarily tectonically controlled. The only possible climatic control may be reflected by the upwards change in sediment type that culminated in the fine grained lacustrine sedimentation of the lower Mount Celsius Supergroup (unit 9). Although this basin-wide change might have been due to decrease of river discharge caused by climatic change, it could also be the result of decrease of source area relief, reflecting a decrease in tectonic uplift rates.

v) Gauss Basin disappearance and Ymer Ø phase

The disappearance of the Basin was clearly related to the Ymer Ø phase of deformation, and both were therefore primarily controlled by tectonic processes.

General comment

Although, in common with most geologists, we tend to think tectonically rather than climatically, there seems little doubt in this case that the major events of the Devonian sedimentary record in East Greenland were the result of the action of tectonic processes. In order to examine the nature of these we shall now consider the broader tectonic context in which the Devonian sediments occur.

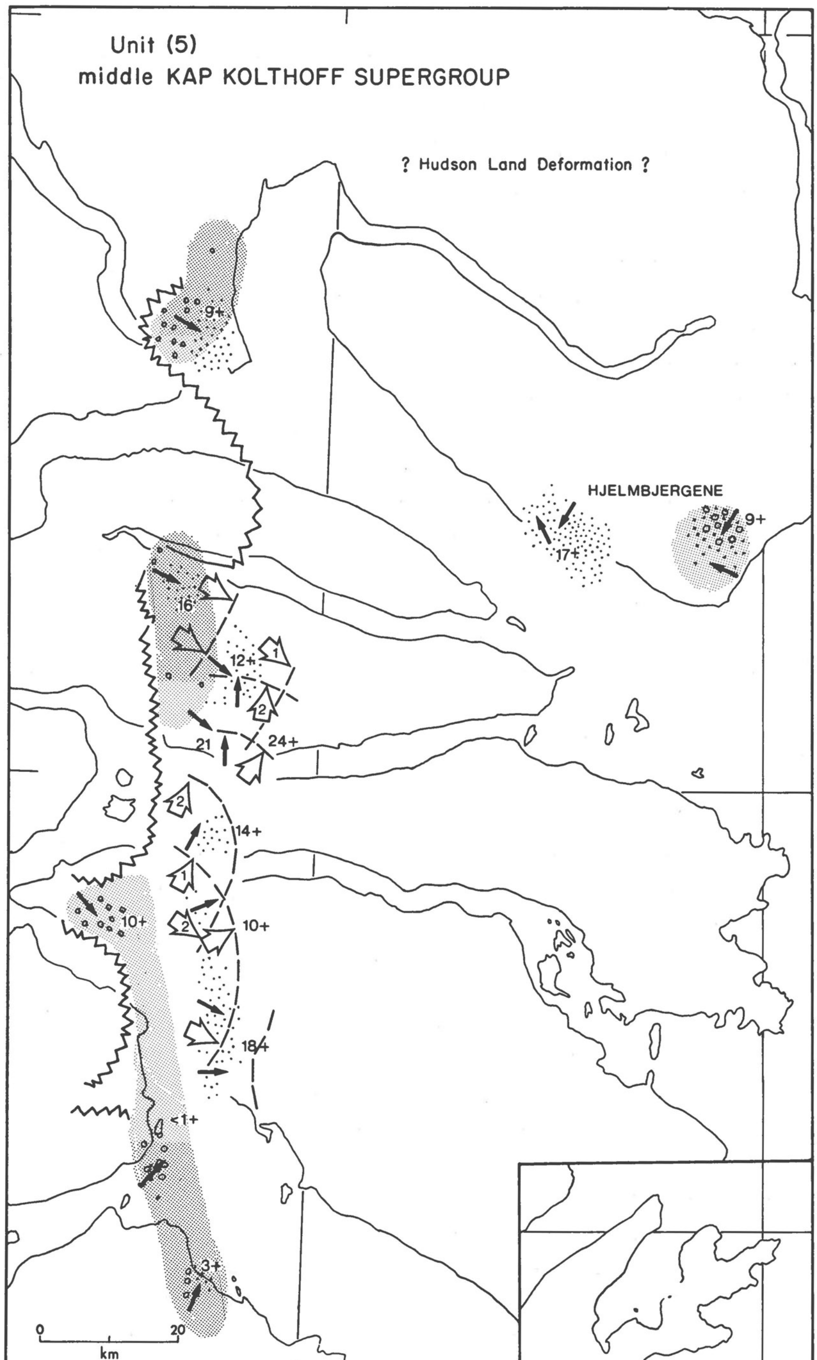

Fig. 27. Standard area map for Unit 5 (middle Kap Kolthoff Supergroup). Conventions explained in caption of Fig. 24.

UNDERLYING TECTONIC PROCESSES

Regional tectonic sequence in Central East Greenland

Sources of information

Two major reviews of East Greenland geology by JOHN HALLER have appeared since our field work was completed (HALLER, 1970, 1971). These accounts, beautifully illustrated with maps and photographs, do much to bring together and review the results of the ground surveys and aerial reconnaissances carried out on Dr LAUGE KOCH's expeditions which had continued until 1958.

While we were carrying out our field work, the Geological Survey of Greenland began a five year programme of field work in the Scoresby Sund area (70°–72°N). HENRIKSEN & HIGGINS (1976) have provided a systematic review of the East Greenland Caledonian fold belt generally, and included much in the way of new material and ideas from this latest programme of work.

All these reviews accept the notion that the East Greenland coastal region was the site of a distinctive tectonic belt in Palaeozoic times. We shall concern ourselves in this review with the southern part of this belt (70°–76°N) nearest to our Devonian sediments that occur between 71° and 74°N.

General outline of the Precambian to Devonian sequence

Two tectonic windows (HENRIKSEN & HIGGINS, 1976), in western Gåseland (70°30'N) and in Charcot Land (72°N) reveal areas of gneissose basement. Radiometric ages from these windows suggest important mobilisation about 2000 m.y., or earlier, and this has been referred to the Archaean (HENRIKSEN & HIGGINS, 1976, p. 185).

Other crystalline metamorphic rocks form about half of the outcrop area in the East Greenland coastal zone, between 70° and 76°N. Whereas HALLER (1970, 1971) regarded these rocks as the infrastructure of Caledonian (broadly Silurian) orogenesis, and essentially deformed at that time, HENRIKSEN & HIGGINS (1976) stress, particularly on the basis of radiometric age determinations, that these metamorphic complexes "retain characteristics of several pre-Caledonian orogenic events". They suggest an age range of 1200–900 m.y. for these events (HENRIKSEN & HIGGINS, 1976, p. 185) which they regard as locally more important in terms of mobility than any later events, including Palaeozoic, Caledonian ones.

The critical marker that identifies, with certainty, Caledonian events in this area is the major conformable sequence comprising the Eleonore

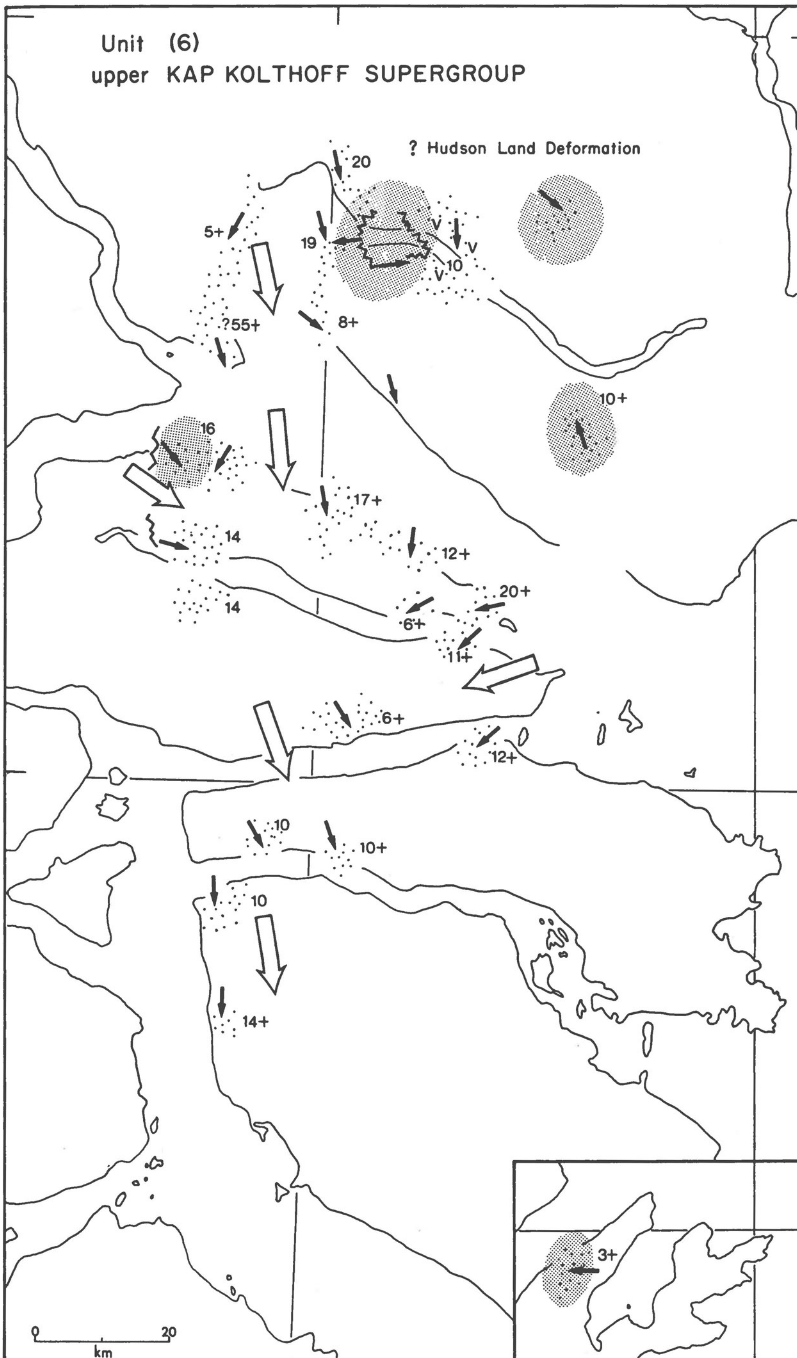

Fig. 28. Standard area map for Unit 6 (upper Kap Kolthoff Supergroup). Conventions explained in caption of Fig. 24.

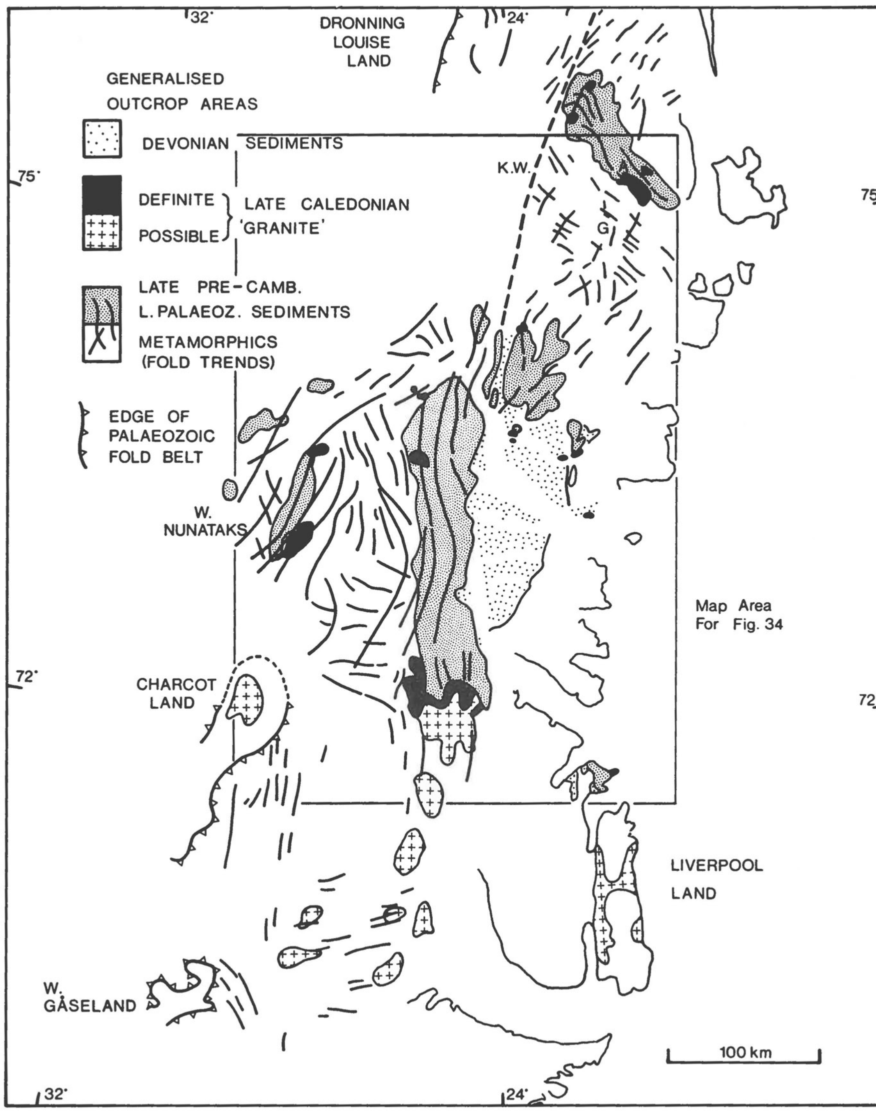

Fig. 29. Sketch map showing certain features of East Greenland Fold Belt between about 70° and 76°N – based on Tectonic/Geological Map of Greenland, 1970 by the Geological Survey of Greenland (1:2 500 000), with additions from HENRIKSEN & HIGGINS (1976). A: Ardencaple Fjord, G: Grandjeans Fjord, KW: Kong Wilhelms Line. Only the outermost coastline is shown.

Bay and Tillite Groups and the Cambro-Ordovician strata. This sequence totals up to 17 km in thickness, and accumulated from late Precambrian to lowermost Upper Ordovician times (HENRIKSEN & HIGGINS, 1976). The lateral continuity and lithologies of the subdivisions, at least of the

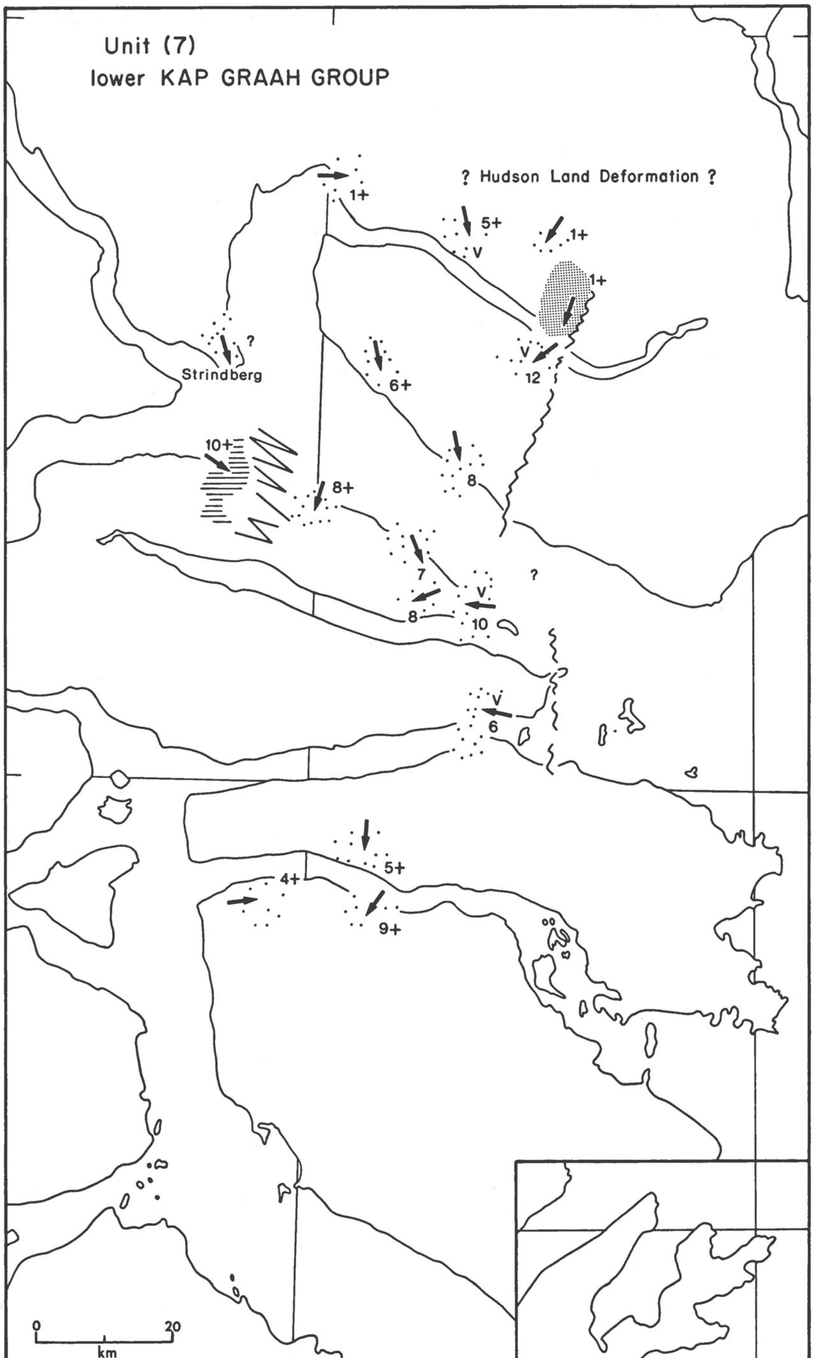

Fig. 30. Standard area map for Unit 7 (lower Kap Graah Group). Conventions explained in caption of Fig. 24.

upper parts of this sequence, suggest a very extensive basin of deposition, perhaps extending 1000 km from south to north (HALLER, 1970, Fig. 22). This implies that the present more localised outcrop configuration, and the similarity of that configuration to the outcrop of Devonian rocks, must reflect later tectonism, broadly in Silurian and/or Devonian times.

The obvious folding and faulting of the Eleonore Bay, Tillite and Cambro-Ordovician strata must have occurred after the lowermost Upper Ordovician, and mainly before deposition of the Devonian rocks. It is therefore of Caledonian age. HALLER regarded this deformed material as the "superstructure" of the Caledonian orogenic pile, in contrast with the crystalline "infrastructure". For general analytical purposes he distinguished three episodes with the Caledonian orogeny in East Greenland:

(i) Caledonian main orogeny (broadly Silurian)
(ii) Late Caledonian spasms (Devonian)
(iii) Minor succeeding episodes (Carboniferous).

Plutonic intrusive bodies make up about 5 % of the outcrop area between 70° and 76°N. They are predominantly of granitic and granodioritic composition. Some of them are demonstrably of Caledonian rather than earlier age, because they have intruded rocks of the Eleonore Bay Group. Many others are similar in type, but not so directly dateable (HENRIKSEN & HIGGINS, 1976, Fig. 187).

Features of the terrain west of the Devonian outcrop area

The remarkably clear internal stratigraphy of the upper Eleonore Bay, Tillite, and Cambro-Ordovician strata has made it possible to map with precision the folding and faulting of these strata in some areas. A detailed, contoured, structure map (HALLER, 1970, pl. XLI) has been made for this basement superstructure along most of the western border of the Devonian outcrop area. This map shows a pattern of more or less elongated domes and basins, trending in a north-south direction and with a strong overall easterly dip. The folds are generally open and imply only minor east-west shortening, of the order of 5 % at its greatest (EHA, 1953, p. 91). Crustal compression was not therefore a significant feature of the Caledonian main orogeny as far as this part of its superstructure was concerned. Indeed, in northern Scoresby Land (72°20′N), tensional effects, probably a component of the "late Caledonian spasms" (HALLER, 1970, p. 119) produced normal faults indicating a net extension of about 30 % (FRANKL, 1953, p. 50), considerably greater than the shortening of the Caledonian main orogeny.

Fig. 31. Standard area map for Unit 8 (upper Kap Graah Group). Conventions explained in caption of Fig. 24.

Further west, in the nunatak zone (28°W, 73°N), an isolated area of the superstructure sequence was deformed into relatively simple, open folds, trending north-south.

In the inner fjord area, between the main fjord area and the nunatak zone, is the "Central Metamorphic Complex" made classic by HALLER's work on its migmatite structures (e.g. HALLER, 1970). Although HALLER regarded these structures as dating from the Caledonian main orogeny, HENRIKSEN & HIGGINS (1976), largely on the basis of work further south, suggest that they may have been Precambrian. The question of the age of the main metamorphism and migmatite movement is not important here, because there seems little doubt that these events were over by the onset of Devonian sedimentation, at least in the areas preserved today. Certainly we can see no similarity between the patterns of Devonian sedimentation we have discovered, and the scale of the structures within the Central Metamorphic Complex. However if the Complex, at least round 74°N, is considered in relation to the superstructure outcrops both to the west and to the east, it forms a broad anticline, and it may be that this structure arose during Silurian times, and perhaps also during Devonian times, when it could have acted as a source for Devonian sedimentation. In position and north-south trend, it seems right to have acted as a western source for either Vilddal or Gauss Basin sedimentation.

Examination of the western unconformity of the Devonian outcrop area shows the amount of erosion that had taken place along the zone of unconformity between the lowermost Upper Ordovician (youngest pre-Devonian rocks known), and the accumulation of middle Devonian Gauss Basin sediments. In most cases, the basal Devonian erosion surface had cut into Ordovician or Cambrian rocks. This means that commonly no more than 2 km or 3 km of bed-rock had been eroded by the time Devonian sedimentation began, assuming that the Ordovician strata were the last basement rocks to be deposited in this area. In south-western Ymer Ø, erosion reached the Quartzite Series of the Upper Eleonore Bay Group, requiring removal of about 6 km of material, and south of Ella Ø, erosion commonly reached the Limestone-Dolomite Series of the upper Eleonore Bay Group, requiring removal of up to 5 km of material. However nowhere along this unconformity zone, did erosion reach the Lower Eleonore Group of the Central Metamorphic Complex before Devonian sedimentation. At the present day, erosion has exposed large areas of the Central Metamorphic Complex, requiring removal of at least 17 km of the intervening Eleonore Bay, Tillite and Cambro-Ordovician strata, only 40 km to the west of the present Devonian outcrop. Our analysis of the western unconformity suggests that much of this uplift may have taken place during Devonian sedimentation.

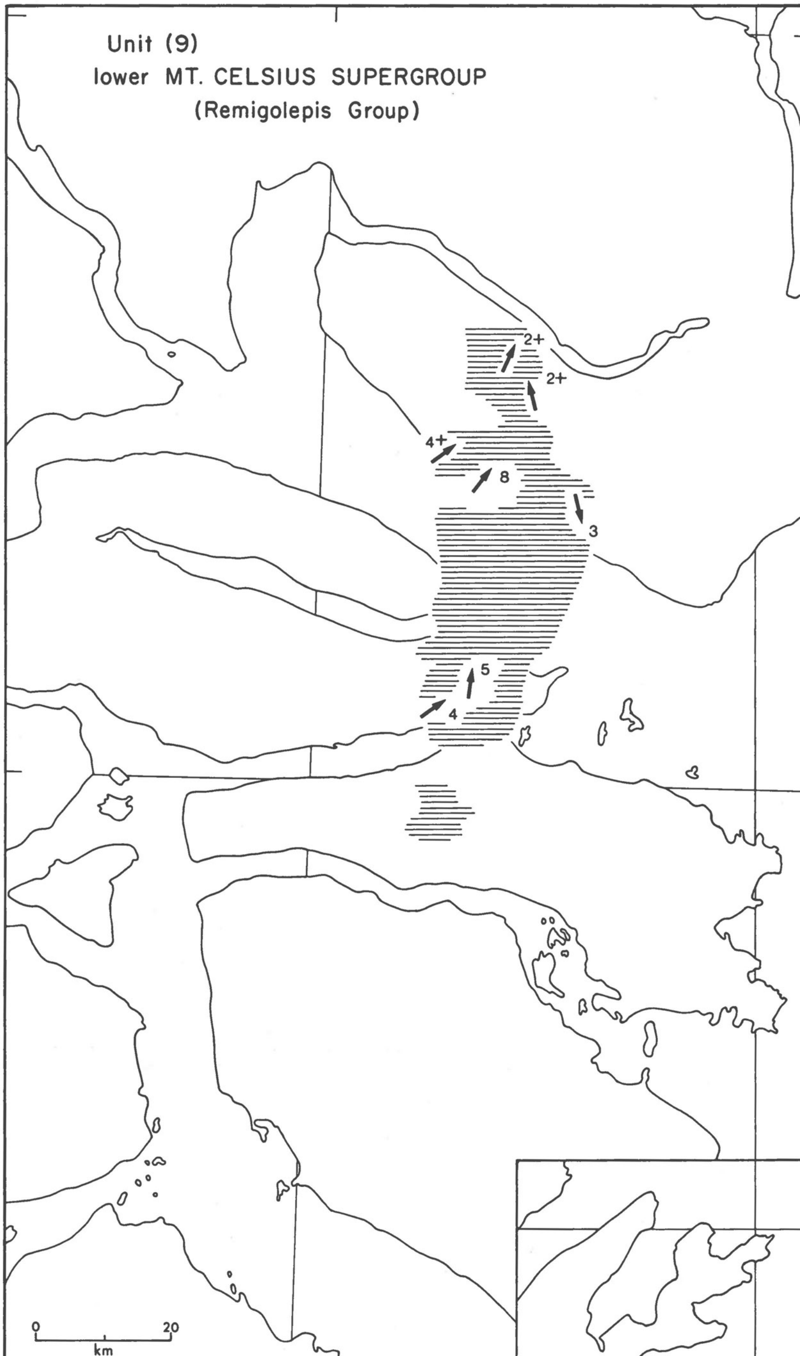

Fig. 32. Standard area map for Unit 9 (lower Mount Celsius Supergroup, Remigolepis Group). Conventions explained in caption of Fig. 24.

Further evidence of source area uplift is provided by plutonic intrusions, demonstrably of Caledonian age, forming a major lineament in the main Eleonore Bay Group outcrop area, particularly in the Stauning Alper (72°N), and Grejsdalen (73°35′N), and another lineament of plutonic bodies, broadly of granitic composition, in the nunatak zone to the west.

Features of the terrain north of the Devonian outcrop area (Fig. 29)

Outcrops of the Eleonore Bay, Tillite and Cambro-Ordovician strata form a northern fringe round the main Devonian outcrop area, although this fringe is not as continuous as the western fringe just described. Eleonore Bay Group rocks have also been found in a fault graben in the Ardencaple Fjord area (75°30′N), some 150 km north of the main Devonian outcrop area.

The northern edge of the Devonian outcrop area is complicated in map outline because of the large number of northerly and north-northeasterly trending faults that cut it. As discussed in an earlier section, some of these faults appear to have been active during the Kap Franklin Deformation, between the development of the Vilddal and Gauss Basins, and probably they were also active during Gauss Basin sedimentation. In the western part of the northern outcrop of the Devonian unconformity, minimal amounts of the "basement" were eroded before the first Devonian sedimentation which generally accumulated on Ordovician strata. In central and eastern Hudson Land, however, erosion cut down into the lower parts of the Upper Eleonore Bay Group, at least 6 km below the basement surface. The local changes of the level of erosion reached within the stratigraphy of the Eleonore Bay Group suggest that some faulting and/or local folding may have preceeded the first Devonian sedimentation. Within the "inlier" of western Moskusoksefjord, a core of "granite" is surrounded by metamorphic gneisses and schists, and areas of Tillite Group and Cambro-Ordovician strata. Complex folding and faulting must have preceded unconformable sedimentation of "Inlier Konglomerat 2" (unit 2), which was, in turn, tilted before later Kap Kolthoff sedimentation. In central Hudson Land, north of Laffons Bjerg, (73°50′N), Koch & Haller (1971) map another locality with Devonian sediment resting unconformably on metamorphic rocks, but this is the only such area known in East Greenland. We think it significant that both these areas of deep erosion, apparently impying strong local uplift, are in the area of Hudson Land faulting.

The Grandjean Fjord metamorphic complex extends northwards between the Eleonore Bay Group outcrops at about 74°N, to those of the Ardencaple Fjord area, between 75°20′N and 76°N. Haller regarded

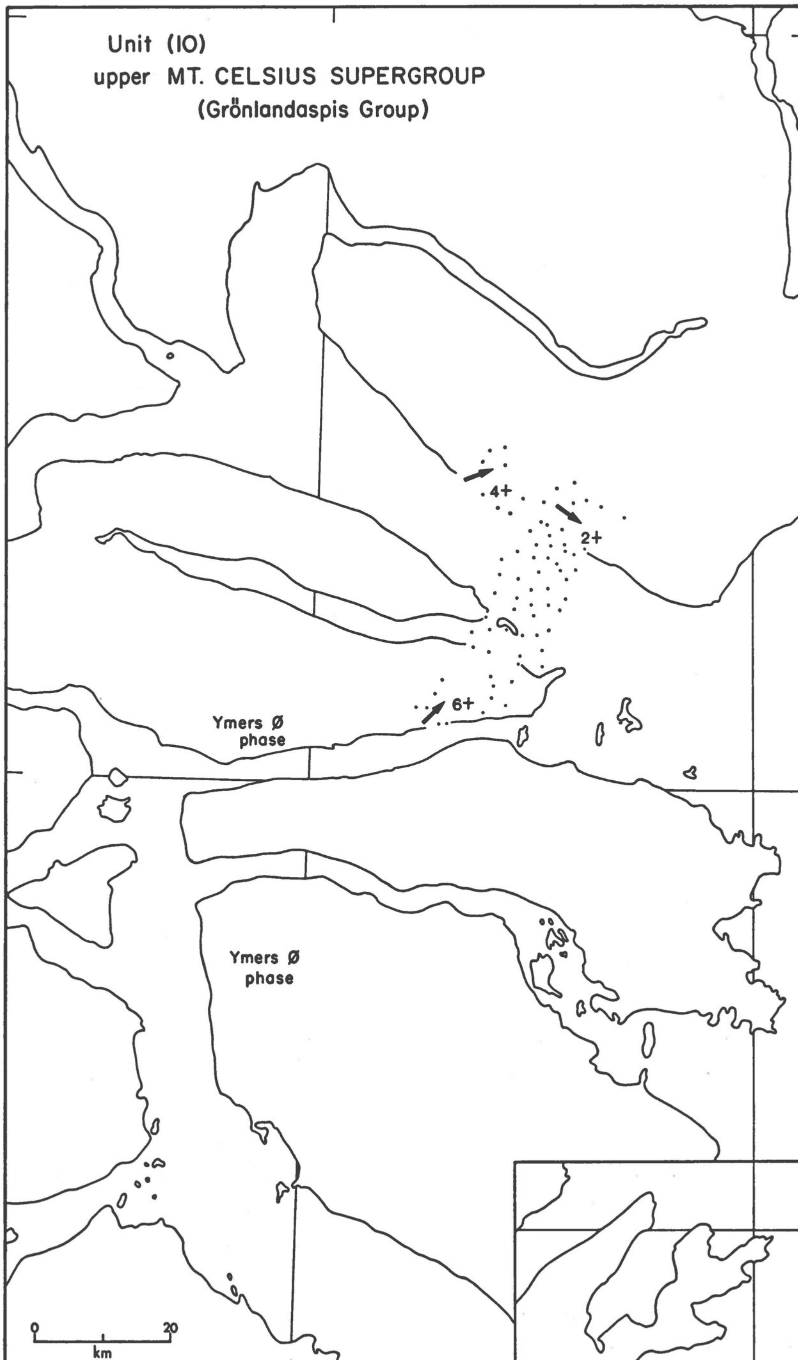

Fig. 33. Standard area map for Unit 10 (upper Mount Celsius Supergroup, Grönlandaspis Group). Conventions explained in caption of Fig. 24.

the deformation and metamorphism of the complex as main and late Caledonian events, whereas HENRIKSEN & HIGGINS (1976) suggest that much of this crustal activity may have been earlier. However both agree that a late stage, north-west trending, series of cross-folds formed at the same time as similar trending folds and thrusts in the Eleonore Bay Group sediments of Ardencaple Fjord, and there can therefore be no doubt that these are broadly Caledonian features. HALLER (1970) concluded that they belonged to the "Late Caledonian spasms", of Devonian age, and formed in the "northern high ground" which rose during sedimentation of the Devonian in a down-flexed graben-like area that similarly trended north-west (HALLER, 1970, p. 98, Fig. 40).

In this northern terrain, the most distinctive plutonic bodies that are known to be of Caledonian age (HENRIKSEN & HIGGINS, 1976, Fig. 187), are those that intruded the Eleonore Bay Group sediments of Ardencaple Fjord. Other bodies, of smaller size, occur in the west Moskusoksefjord Inlier, and in Stenos Land (74°24'N).

Features of the terrain east and south of the Devonian outcrop area

The eastern edge of the main Devonian outcrop area is formed by a series of normal faults that bring down to outcrop level successively younger Carboniferous, Permian and Mesozoic stratigraphic units eastwards. In Gauss Halvø and Hudson Land, this zone trends north-south, and is complicated by the presence of Devonian inliers, of great stratigraphic importance, to the east of the so-called "post-Devonian main fault" (VISCHER, 1943). These inliers form the Kap Franklin, Gastisdal and Nordhoeks Bjerg Devonian outcrop areas.

To the south, along the eastern edge of the Devonian outcrop, the "post-Devonian main fault" trends south-westwards across Geographical Society Ø and Traill Ø, forming the western fault of an apparently simple series of normal faults, some of which are demonstrably post-Cretaceous in age. This series of step faults seems to pass southwards into the north-western limb of the Jameson Land Mesozoic basin.

South of Kong Oscars Fjord, the "post-Devonian main fault" runs southward, bringing the Caledonian and possibly earlier terrain into contact with the western edge of the late Palaeozoic and Mesozoic Jameson Land basin. The eastern edge of this basin is bounded by the Wegener Halvø, Canning Land, Liverpool Land horst. Wegener Halvø and Canning Land provide isolated exposures of Devonian strata, characteristically linked with the Eleonore Bay, Tillite and Cambro-Ordovician strata. This again makes the point that the distribution of these older strata is generally closely similar to that of the Devonian strata, and must reflect a similar, or the same, pattern of crustal movements. The unconformable base of the Kap Fletcher Formation rests on Upper Eleonore Bay Group carbonates (CABY, 1972, p. 26), probably the Limestone-Dolomite Series, and Tillite Group and Cambro-Ordovician strata have been discovered nearby (CABY, 1972, p. 25). CABY's analysis of the Eleonore Bay Group structures demonstrates the evidence for crustal extension, probably associated with large westward translation. He also notes strong evidence that the Kap Wardlaw granite of Canning Land, and its dykes, were emplaced during a late stage of this deformation sequence.

Further north, other small plutonic bodies, broadly of granitic composition, are present on Ankerbjerg (73°35′N), intruding Eleonore Bay Group rocks, and on Høgboms Bjerg (73°35′N) and Kap Franklin (73°15′N) intruding Devonian Vilddal Supergroup sediments. These small bodies are directly dateable by their igneous contacts, but there are much larger areas of apparently similar outcroups, for example in Liverpool Land, that may also date from the same periods of emplacement.

Wrench tectonics—the underlying control?

Outline of the meaning of wrench tectonics

In the final sections of this paper, we shall discuss the major wrench tectonic model that we believe provides a powerful basis for understanding the varied observations we have been describing and analysing.

Although the wrench tectonic term is a genetic one, involving a crustal stress pattern where greatest and least stress directions act horizontally, the practical definition is a kinetic one, in which the greatest deformational movement is horizontal or parallel to the strike of one or more distinct zones of deformation. These zones commonly contain major faults, and the scale of the deformation system is often so great that it appears certain that it extends to great depths within the lithosphere. WILCOX, HARDY & SEELY (1973) have provided a valuable review of these tectonic systems, and use both laboratory models and geological examples to show that wrench systems can be classified into "simple parallel", "convergent" or "divergent", depending on whether the crustal blocks appear simply to have slid past each other, or showed also components of movement perpendicular to the major fault or zone. Depending on the strength and sense of these components, as well as the heterogeneity and stress rate in the system, various combinations of the following structures are characteristic of wrench zones:

(i) the major wrench faults
(ii) conjugate strike-slip faults
(iii) tension faults
(iv) en echelon folds

Any such combination of structures may be further complicated over a period of time, by continued application of stresses, perhaps different in direction, on the already deformed, and thoroughly non-homogeneous, crust.

Other Devonian areas

Evidence is accumulating of the important role of wrench tectonics in the Devonian evolution of a number of other areas of the Caledonian-Appalachian orogenic belt. We shall below briefly describe some of this evidence, starting in the north.

(i) *Spitsbergen* (FRIEND & MOODY-STUART, 1972; HARLAND and others, 1974). Here the distribution and derivation pattern of stratigraphical units, subsequent en-echelon folding, and strike-slip faulting are all consistent with left-lateral strike slip faulting along directions parallel to the northerly basement fold trend. The Billefjorden Fault Zone contains much the biggest exposed example of the strike-slip faulting.

(ii) *Western Norway.* A number of distinct small basins of Devonian age existed in Norway (NILSEN, 1973). Of these two, Hornelen and Kvamshesten, show evidence of a wrench tectonic regime (STEEL, 1976). Indeed in the case of Hornelen (STEEL, 1976; STEEL & GLOPPEN, 1980), there is evidence for a) a systematic migration of the locus of deposition, achieving a total integrated thickness of the order of 25 km of sediment, b) strongly asymmetric basin fill, c) dominance of longitudinal fill, d) mismatch of pebbles with the nearest apparent source area, and e) systematic migration and skewing of marginal fan bodies. All these features are explicable in terms of major right-lateral movement about a boundary fault, not yet located in outcrop in the basement to the north, but apparently trending parallel to the basement fold trends. This evidence for syn-depositional wrench tectonics appears to be unique within the Devonian record of the Atlantic borders, and must indicate an usually strong dependence of sedimentation on strike-slip effects at the surface.

(iii) *Scotland and northern Ireland.* The Great Glen Fault of the mainland of Scotland has long been claimed to be a major strike-slip fault with its largest movement in Devonian times. It is thought to extend into the Shetland Islands in the north (MYKURA, 1975; DONOVAN and others, 1976), and southwards into Ireland (PITCHER & BERGER, 1972). There is still disgreement about the sense of faulting movement (e.g. MYKURA, 1975; STOREDTVEDT, 1975) i.e. whether movement was left- or right-lateral. Much of the argument about this has been based on doubtful evidence of match, or mismatch, between features on both sides of the fault, which may also have had a significant component of dip-slip movement (e.g. CHINNER, 1978). Whatever the movement, very different Devonian successions have been juxtaposed in the Shetland Islands (MYKURA, 1976). In the Midland Valley of Scotland, BLUCK (1978) has suggested that left-lateral movement of the northern (Highland) Boundary Fault may have controlled sedimentation in Upper Devonian times.

(iv) *Canadian Appalachians.* The northern segment of the Appalachians is traversed by a large number of major faults, striking at low angles or parallel to the general direction of the orogenic belt. Although most of these suffered major right-lateral strike-slip movement in post Devonian times, there is also evidence of Devonian strike-slip movement, probably in a left-lateral sense (WEBB, 1969). POOLE (1976, p. 124) describes transcurrent faulting ("left lateral?") as a characteristic feature of the Devonian Acadian orogeny of this area.

Wrench processes in the orogenic context

It is now generally accepted that, in Devonian times, the Caledonian-Appalachian orogenic belt was the site of major continent-continent collision, at least in its Caledonian segment (DEWEY, 1969). The widespread occurrence of strike-slip faulting at this time has been recognised by some (e.g. HARLAND, 1965). Indeed, HARLAND (1965) suggested that this strike-slip motion was generally left-lateral, parallel to the orogenic belt, and MORRIS (1976) has assembled palaeomagnetic data which are consistent with a Middle Devonian, left-lateral movement of about 1800 km. A present-day analogue of the continent-continent collision situation, with mobility along numerous strike-slip fracture zones, is the Himalayan complex of mountain belts, resulting from the collision of Eurasia and India (MOLNAR & TAPPONNIER, 1975).

When FRIEND (1969) reviewed Old Red Sandstone sedimentation in the North Atlantic borders, he assembled evidence for strong vertical crustal movements in a large number of distinct basins, varying in local timing and geometry. More recently, as has been briefly summarised above, stratigraphical and sedimentary evidence has also been accumulating showing the importance of wrench faulting, both in producing and deforming the sediments. So a pattern now emerges in which combinations of vertical and horizontal motion on major lithosphere transcurrent fractures provide the link between continent-continent collision and the history of the Devonian sedimentary basins.

Another recent approach that is highly relevant relates the action of the major transcurrent faults, deep in the crust, to the genesis and emplacement of "granites" (LEAKE, 1978).

It is against this background of rapidly increasing general understanding of crustal and sub-crustal processes, that we now return, in a speculative way, to the East Greenland area.

Speculation on the underlying tectonic events in East Greenland

We now suggest, in the context of Devonian continent-continent collision, and major lithosphere transcurrent fracturing, a sequence of events that may have occurred in East Greenland. Our major suggestion is that the Devonian tectonic situation was dominated by a series of fracture zones, extending downwards probably at least to the base of the crust, similar to those described from the Indian-Eurasian collision zone (KRESTNIKOW & NERSESOV, 1964; MOLNAR & TAPPONNIER, 1975). Although probably largely generated by wrench stresses, and periodically showing some component of strike-slip, their surface effects included both vertical and horizontal components of motion. It seems reasonable to suppose that horizontal motions, affecting the whole crust, would locally bring colder crust and hotter mantle together at depth, and so create local pockets, in some cases of cooling, and in other cases of heating, perhaps with at least partial melting (LEAKE, 1978, p. 237). These processes, operating at depth, would tend to produce vertical movements and perhaps volcanicity at the surface, and granite emplacement near the surface.

For modelling purposes, we assume a standard width of 20 km, at the crustal surface, for these "hypothetical fracture zones" (HFZ). We find evidence for four, more-or-less northerly trending zones in our area, using the presence of granite intrusions and other geological lineaments to position them, as follows:

i) Western Nunatak HFZ, based on the presence of granites, and the distinctive supracrustal synclinorium.
ii) Niggli Spids HFZ, based on the presence of granites, and the major boundary between infra- and superstructure.
iii) Kong Oscars Fjord-Nordfjord HFZ, based on the presence of granites, the western margin of the Gauss Basin, and with slight curvature, Kong Wilhelms Line (Fig. 23) of HALLER (1970, p. 100).
iv) Kap Franklin-Canning Land HFZ, based on the presence of granites, Devonian volcanics, and the eastern margin of the Gauss Basin.

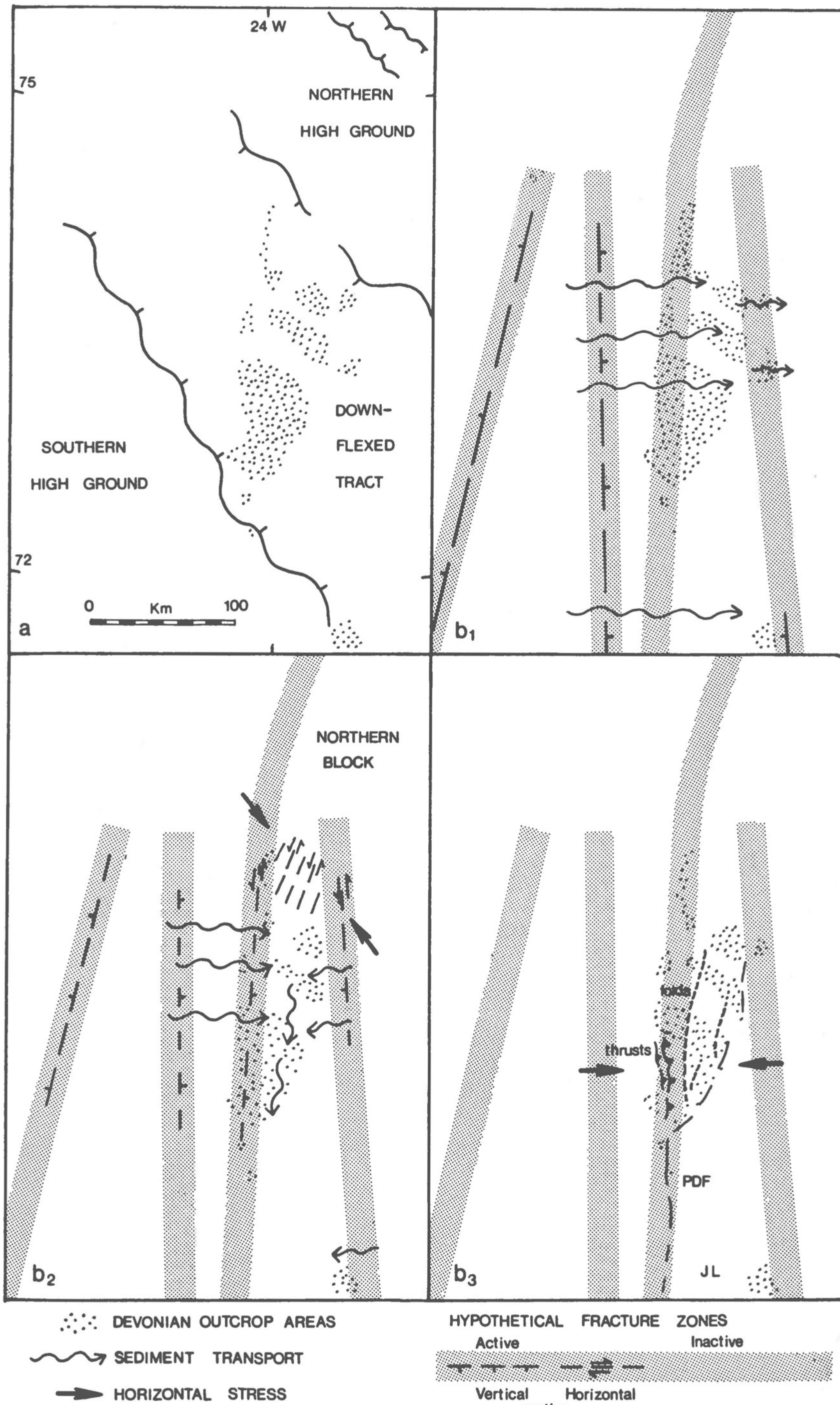

Fig. 34. Sketch maps illustrating suggested development of area of Devonian sedimentation. a) HALLER's suggestion of major late Caledonian structural provinces (HALLER, 1970, Fig. 40). b (i) Development of Vilddal Basin, b (ii) Kap Franklin Deformation, development of Gauss Basin, Hudson Land Deformation, b (iii) Ymer Ø phase.

Fig. 34 attempts to show the possible relationships between the activity of these hypothetical fracture zones and the Devonian sedimentation and deformation. Fig. 34a shows the broad suggestion made by HALLER (1070, Fig. 40) of late Caledonian structural provinces. We find particularly helpful the idea of a northern crustal block, essentially now represented by the Grandjean Fjord metamorphic complex with its late-stage north-westerly fold trend.

We propose three different episodes of activity on the hypothetical fracture zones.

i) *Vilddal Basin episode* (Fig. 34b).

Middle Devonian uplift of the crustal block between the Western Nunatak and Niggli Spids HFZ produced a source area for sediment. The sedimentation was mainly centred in the area of the Kap Franklin-Canning Land HFZ that was inactive at this time, except for the Kap Fletcher volcanicity and some later local uplift in the south.

ii) *Kap Franklin Deformation, Gauss Basin Development and Hudson Land Deformation.*

The same block, between the Western Nunatak and Niggli Spids HFZ, seems to have continued to rise, but major changes occurred to the east in late Middle Devonian times. The Kap Franklin-Canning Land HFZ became active, with granite emplacement and volcanicity. It formed a general eastern margin for the developing Gauss Basin, and was also the site of local folding suggesting left-lateral wrench activity along the HFZ. A western margin for the Gauss Basin formed above the Kong Oscars Fjord-Nordfjord HFZ, where a distinctive escarpment was formed against which the sediment accumulated. Meanwhile in Hudson Land, to the north, major horst and graben formed between the two HFZ, and their structures suggest a general left-lateral wrench regime localised where the block between the two HFZ extended into the major northern block suggested by HALLER (1970, Fig. 40). As this deformation was taking place in Hudson Land, sediment was being eroded from the resulting terrain and deposited further south. This crustal mobility gradually decreased during the Upper Devonian.

iii) *Ymer Ø phase, and later events.*

The story of sedimentation was terminated by the Ymer Ø phase of movements, of approximately early Carboniferous age. Gentle northerly trending folds formed in the centre of the outcrop area, and the much stronger deformation in the Kong Oscars Fjord area suggests motion of the Gauss Basin fill westward over its basement. Both effects probably reflect compression of the whole block between the Niggly Spids and Kap Franklin-Canning Land HFZ, but there may also have been important local movement on the Kong Oscars Fjord HFZ.

It is interesting to note that the "post Devonian Main Fault" later followed the line of two of these HFZ, jumping from one to the other across Traill Ø, and that Mesozoic faulting and sedimentation (Surlyk, 1978) also reflects activity along, and parallel to, the same two HFZ.

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